

NUCLEAR INSTRUMENTS & METHODS

A JOURNAL ON ACCELERATORS, INSTRUMENTATION
AND TECHNIQUES IN NUCLEAR PHYSICS

EDITOR: K. SIEGBAHN - UPPSALA

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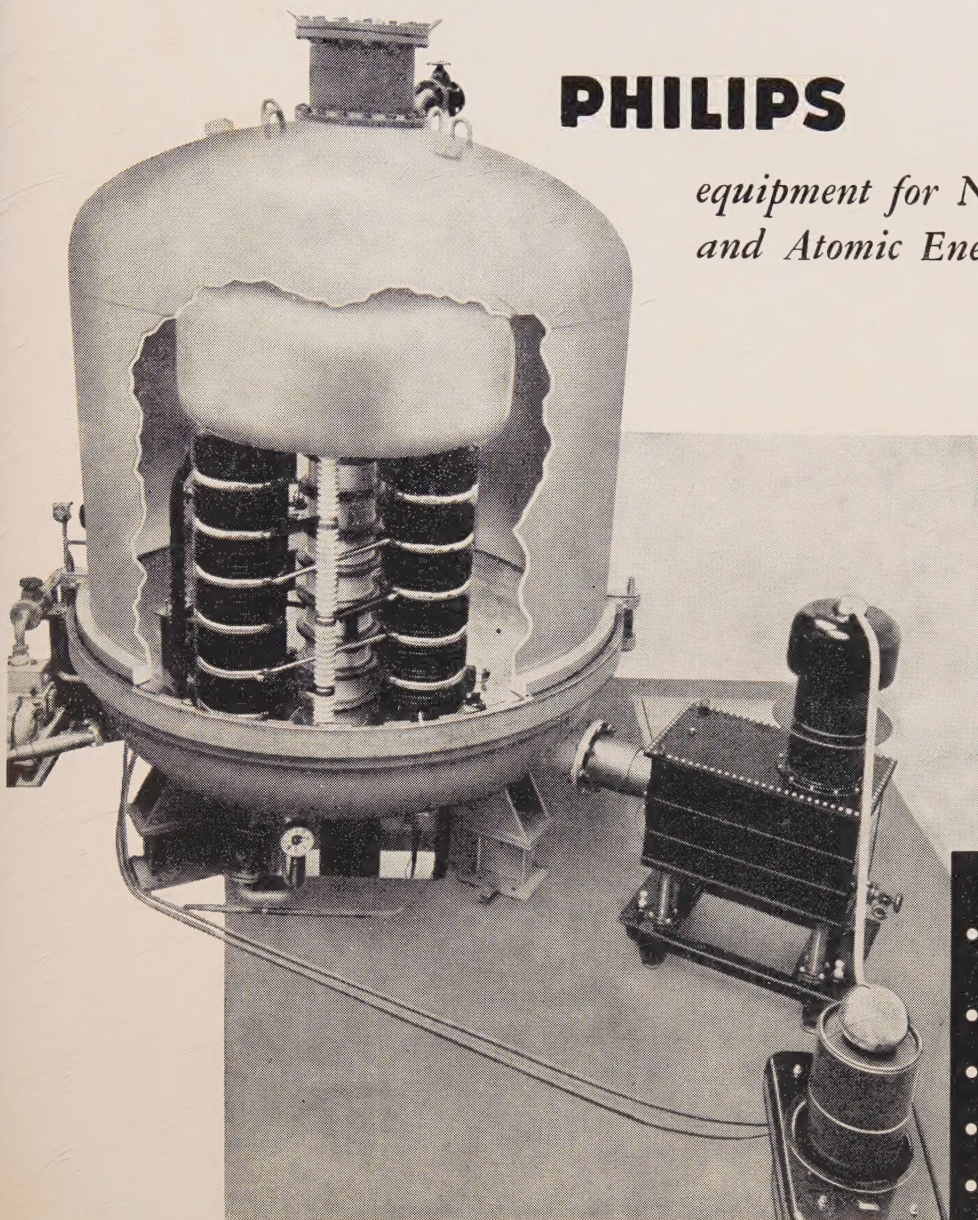
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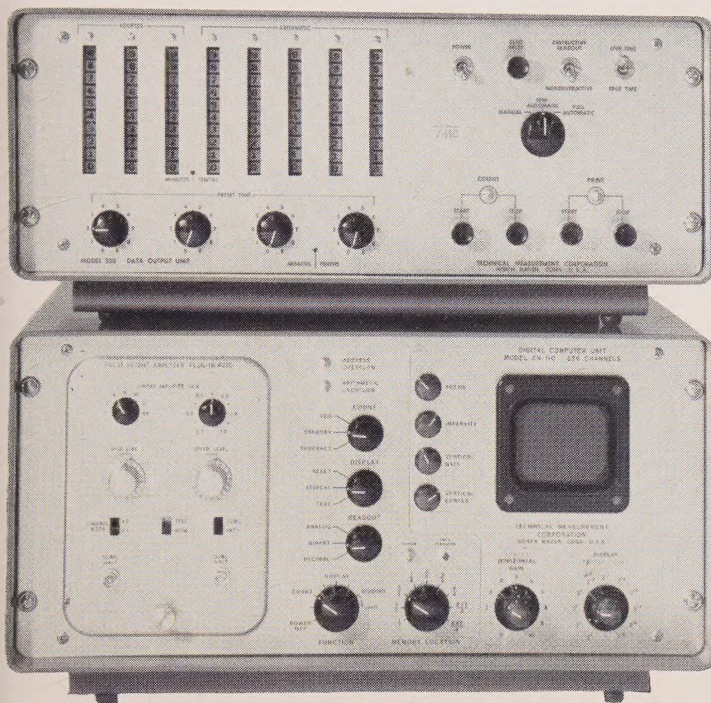
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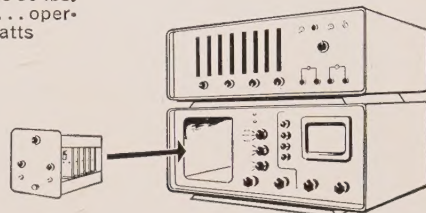
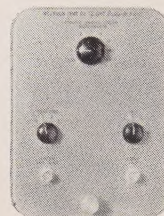


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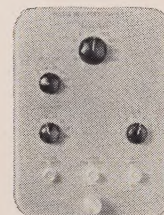
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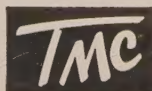
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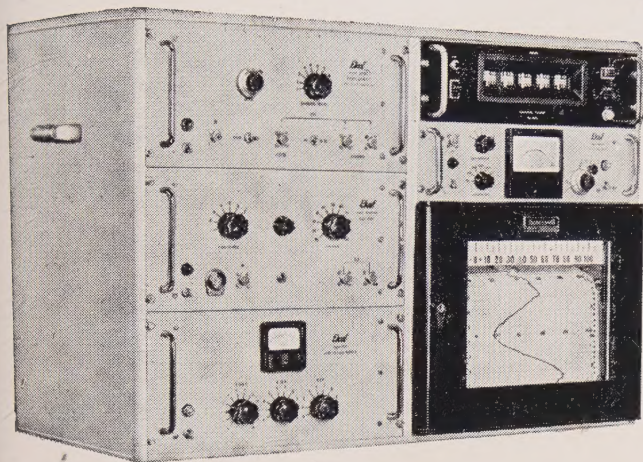
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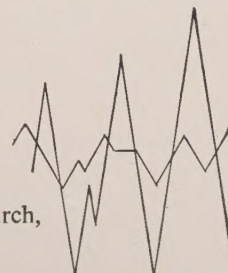
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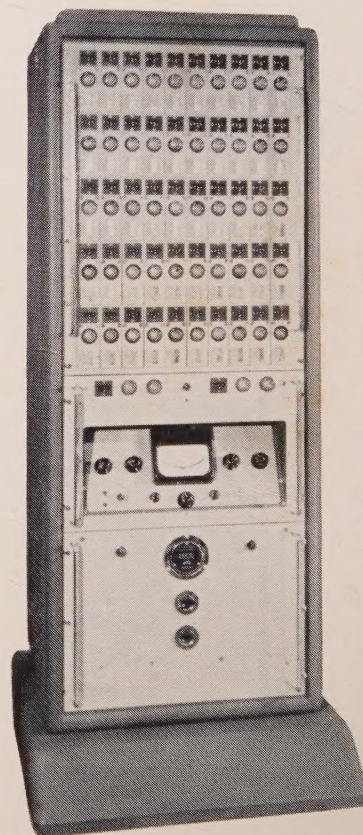
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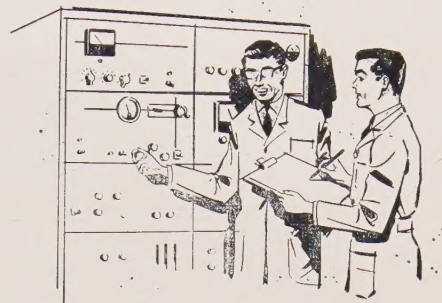
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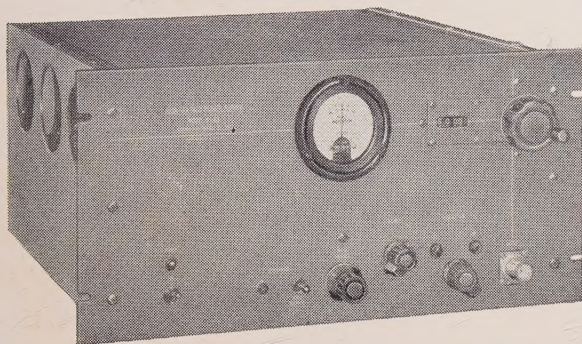
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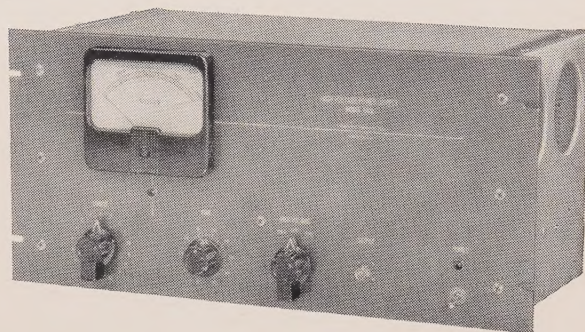
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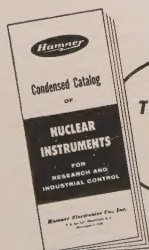
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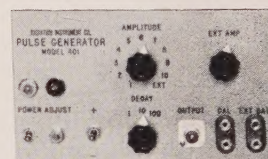
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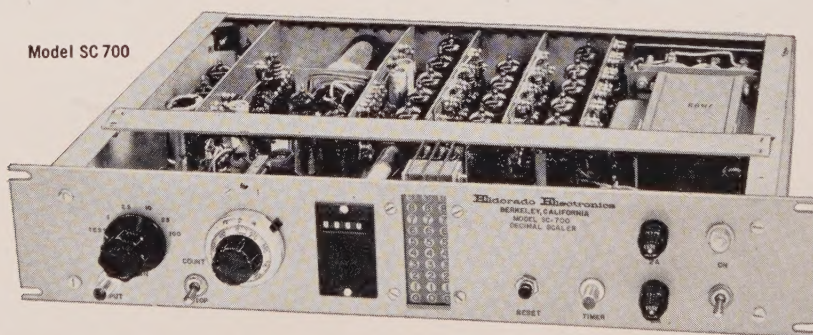
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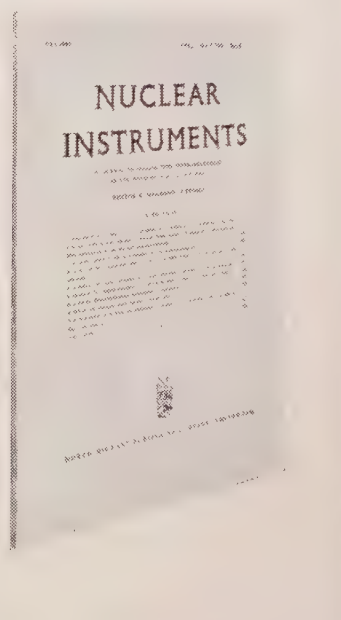
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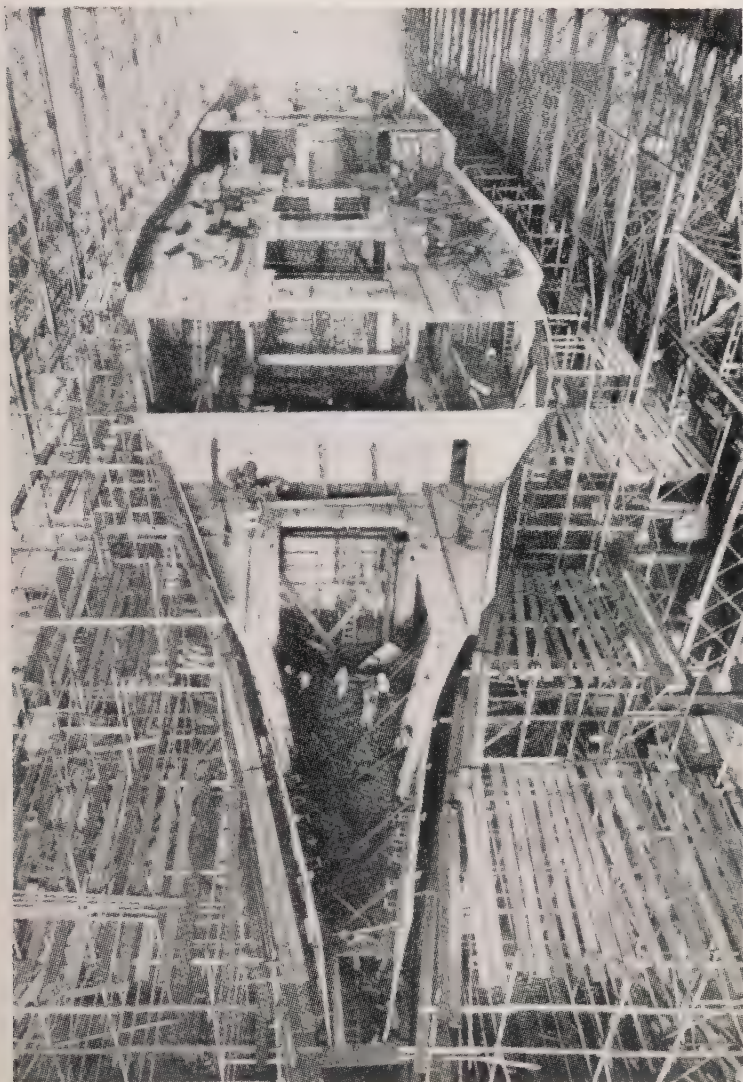
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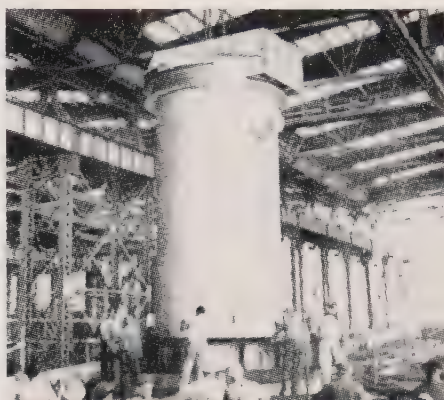
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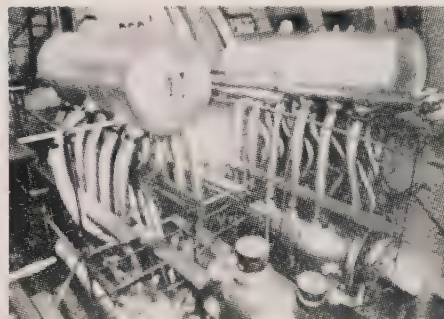
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Energy-transfer Mechanism

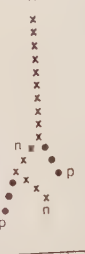
The basic mechanisms by which incident energy is transferred to the target material are of importance. These mechanisms include the "direct effect", which can be described by the target theory of Lea and others, and the "indirect effect" where the energy is absorbed by the solvent and subsequently transferred by radiation-produced intermediates to the solute. Both of these effects take place within the living cell, as shown by irradiation in the wet and dry states. A knowledge of the kinetics of the indirect effect can be important to consideration of the biological effects of ionizing radiation.

Effects of Light and Heavy Particles

The physical structure of microorganisms such as bacteria and viruses has been studied extensively with ionizing radiation. Light particles, such as electrons or x-rays, are easily scattered in matter and may strike the organism from any direction. Analysis of the inactivation from this type of radiation can give a radio-sensitive volume.

Heavy particles, on the other hand, are not easily scattered and travel in straight lines until they are stopped. Analysis of the in-

Characteristics of particles obtainable from Van de Graaff accelerators

	electron	x-ray	proton	deuteron	neutron
Mev	μa	r/min—100cm	μa	μa	n/sec.
1	250	20	50	50	2×10^{10}
2	250	75	50	50	10^{11}
3	1000	1200	200	200	1.2×10^{12}
Typical particle trajectory in target material					

activation data will give a radio-sensitive cross-section for the organism. From data of this type it has been possible to formulate models that agree with structures developed by other experimental methods.

Effects on Man

In addition to fundamental studies on biological materials, there is a great need for better understanding of the effects of ionizing radiation on man. Extensive studies under way on the effects of radiation on animals are providing data that, extrapolated to man, will help greatly in our current problem of providing protection for persons working in radiation environments such as radiation clinics, reactor facilities, and research laboratories. Knowledge of the tolerance dose and the relative biological effects of all the types of ionizing radiation is essential for our safety and for the fulfillment of the ultimate promise of the atomic age.

Necessary Equipment

The radiation equipment necessary to gain this knowledge depends on the major field of interest. The equipment should be variable in energy, should produce all of the particles which are of interest, and should have sufficiently high outputs to produce data in a reasonable period of time. The Van de Graaff® is such a tool. The energies and types of particles it can provide are shown in the table above, with diagrams of their typical modes of energy transfer in matter. The particle energy can be varied from the maximum shown to approximately one tenth of this value. The current is continuously variable from a remote control station. Installation is relatively simple, and the ease of operation and flexibility make it an ideal source of ionizing radiation for biological research.

Write for informative reprints on the effects of charged particles on bacteria.

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DOUBLE MODERATOR NEUTRON DOSIMETER†

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A moderated BF_3 detector was developed for measuring fast neutron dose, flux and average energy in the laboratory. It is being used for measuring dose in field conditions as well, in spite of its directional cylindrical geometry and its weight, because it is very sensitive to neutrons and quite

insensitive to gamma radiation. This instrument, called the “double moderator” and consisting of a “fluxmeter” and a “dosimeter”, was calibrated with monoenergetic neutrons from an accelerator and with neutrons from radioactive sources. Several applications are described.

1. Introduction

Several types of moderated neutron detectors have been employed for making neutron measurements. Before describing the double moderator neutron dosimeter a brief resume will be given of a few similar detectors described in the literature.

The Long Counter¹⁾, developed by Hanson and McKibben in 1947, has been used widely for measuring neutron flux in the energy range 0.025 to 14 MeV. It is a moderated BF_3 detector used with its axis of cylindrical symmetry passing through the neutron source.

In 1953 M. E. Mandl employed a paraffin sphere²⁾ containing indium foils for measuring average neutron energy. She checked her measurements against theoretical predictions.

D. S. Young in 1955 developed a method³⁾ for measuring average neutron energies of radioactive neutron sources. He employed a BF_3 tube in the center of paraffin cylinders of various diameters to find the maximum counting rate for a particular neutron source. He used a calibration curve of paraffin thickness at maximum sensitivity versus neutron energy to determine the average neutron energy. The axes of these

cylinders were oriented perpendicular to the path of the incident neutrons.

The double moderator⁴⁾ measures neutron flux and dose in the energy range 0.1 to 5 MeV and average energy below 1.5 MeV. The core of this instrument consisting of a BF_3 tube at the center of a paraffin cylinder is called the “fluxmeter” while the assembly consisting of the core and an outer removable shell of paraffin is called the “dosimeter”. The ratio of dosimeter counts to fluxmeter counts is a measure of the average neutron energy below 1.5 MeV and for other energy ranges constitutes an accurate check on the neutron energy spectrum to which the arrangement is exposed.

The starting point in the development of the double moderator was a study made on the response of a BF_3 tube as a function of neutron energy and thickness of the enclosing paraffin cylinders. In the course of this work it was found that the optimum thickness was $2\frac{3}{8}$ inches for a fluxmeter while it was $4\frac{1}{2}$ inches for a dosimeter. Like the arrangement employed by D. S. Young

¹⁾ A. O. Hanson and J. L. McKibben, *Phys. Rev.* **72** (1947) 673.

²⁾ M. E. Mandl, Atomic Energy Research Establishment Report, AERE-T/R-1008 (August, 1952) unpublished.

³⁾ D. S. Young, Los Alamos Scientific Laboratory Report, LA-1938 (July, 1955) unpublished.

⁴⁾ J. De Pangher and W. C. Roesch, *Phys. Rev.* **100** (1955) 1793(A);

J. De Pangher, *Bull. Am. Phys. Soc.*, Ser. II, **2** (1957) 378.

† Work performed under Contract No. W-31-109-Eng-52 between the Atomic Energy Commission and General Electric Company.

the cylinders were oriented with the axes perpendicular to a line from the neutron

this instrument was designed primarily for use in the laboratory no attempt has been made to

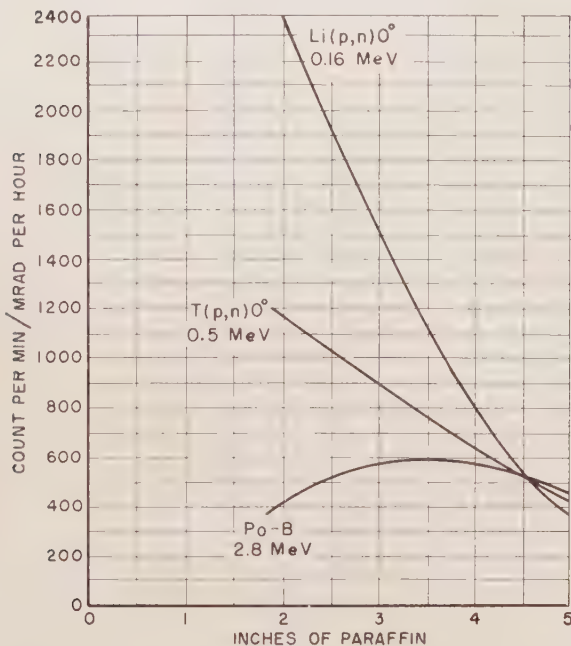


Fig. 1a

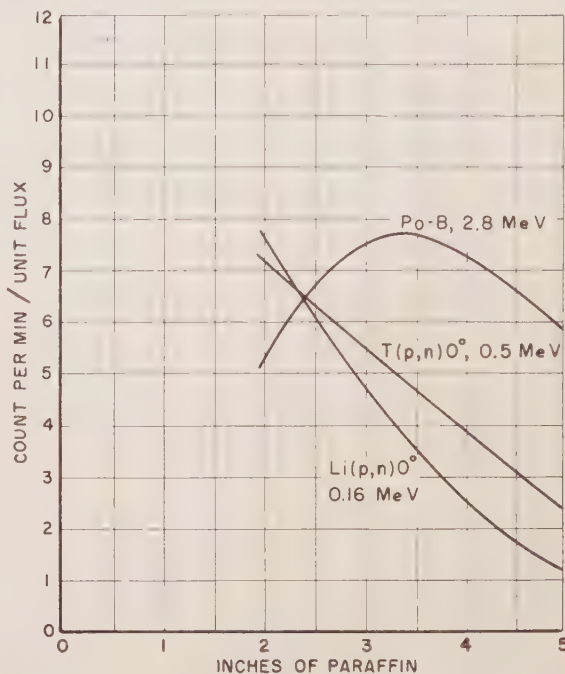


Fig. 1b

Fig. 1a. BF_3 counter in cylindrical moderator: Single collision absorbed dose sensitivity versus wall thickness for three neutron energies. The notation $\text{Li}^7(p,n)\text{O}^\circ$ means $\text{Li}^7(p,n)\text{Be}^7$ at angle of 0° .

Fig. 1b. BF_3 counter in cylindrical moderator: Flux sensitivity versus wall thickness for three neutron energies.

source. Figs. 1A and 1B show the experimental data obtained for a small, rather insensitive BF_3 tube. Later, a larger, more sensitive BF_3 tube was employed in a double moderator whose wall thicknesses were chosen to be close to the values listed above to obtain flux and dose sensitivities independent of the neutron energy.

It is the purpose of this paper to show how this double moderator was calibrated and used for making neutron measurements in the laboratory.

2. Description of Double Moderator and Counting Equipment

The construction of the double moderator and the location and extent of the sensitive volume of the BF_3 tube is shown in fig. 2. The dosimeter weights about 37 pounds and the fluxmeter weights about 13 pounds. Because

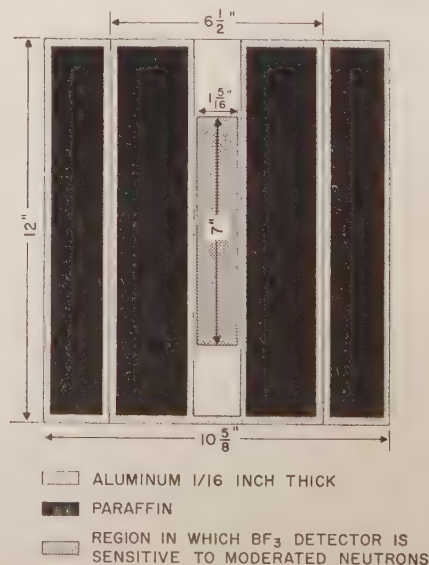


Fig. 2. Construction of the Double Moderator.

hinder thermal neutrons from entering the ends of the detector. Several double moderators,

constructed according to the design given in fig. 2 were tested and yielded responses, for various neutron energies, that agreed within a few per cent. However, one of these using a steel instead of an aluminum case exhibited a reduction in sensitivity of about 50 per cent. The reduction of sensitivity was attributed to the absorption of thermalized neutrons in the central portion of the steel case adjacent to the BF_3 tube.

The counting equipment consisted of a BF_3 tube operated at about 1300 volts, a preamplifier (White cathode follower), a 204-C amplifier operated at maximum gain, a stable high voltage supply and a good quality scaler. About 100 feet of cable separated the preamplifier from the main amplifier.

3. Calibration Procedure

The properties of the double moderator were investigated by comparing it against a long counter with monoergic neutrons and with neutrons from radioactive sources. The long counter was calibrated at about 100 cm from a Ra- α -Be neutron source which had been calibrated at the National Bureau of Standards. All measurements were made with the effective centers of the double moderator and the long counter at about 100 cm from the neutron sources. When calibrated with neutrons from a 2-MeV Van de Graaff accelerator the detectors were exposed simultaneously in the neutron radiation field to minimize drifts in the target yield and to make accurate background subtractions when needed. The beam energy was measured accurately by use of a proton-moment detector, calibrated on the $\text{T}(\text{p},\text{n})\text{He}^3$ and $\text{Li}^7(\text{p},\text{n})\text{Be}^7$ thresholds, to measure the magnetic field strength in the gap of the analyzing magnet. The nuclear reactions $\text{Li}^7(\text{p},\text{n})\text{Be}^7$, $\text{T}(\text{p},\text{n})\text{He}^3$, $\text{C}^{12}(\text{d},\text{n})\text{N}^{13}$, $\text{D}(\text{d},\text{n})\text{He}^3$ and $\text{T}(\text{d},\text{n})\text{He}^4$ were used to supply monoergic neutrons from 79 keV to 14 MeV except for the gaps 1.7–2.3 MeV and 5.1–14 MeV. An SbBe neutron source gave additional information at 25 keV.

Corrections were made for the variation of the sensitivity of the long counter with neutron

energy. The relative efficiency $\eta(E)$ which combines the long-counter data obtained at Los Alamos⁵⁾ and Harwell⁶⁾ is plotted in fig. 3 as a function of the neutron energy E . Above 9 MeV the assumption is made that the curve is linear from $\eta = 0.83$ at 9 MeV to $\eta = 0.70$ at 14 MeV. The last point was established by comparing the yields measured by the long counter on $\text{T}(\text{p},\text{n})$

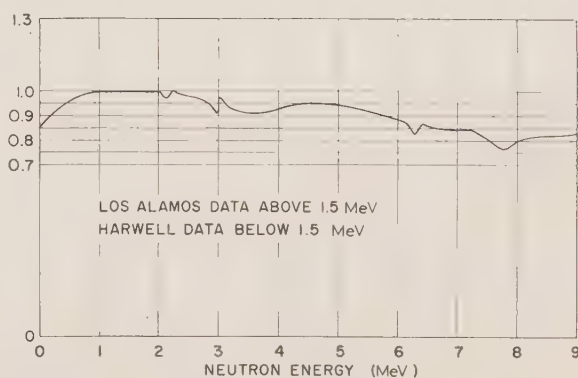


Fig. 3. Relative efficiency of the Harwell and Los Alamos Long Counters.

and $\text{T}(\text{d},\text{n})$ neutrons from the same tritium-zirconium target, and by using the differential cross sections at 0° measured at Los Alamos⁷⁾.

The flux sensitivity of the long counter for monoergic neutrons of energy E is given by

$$S_L(E) = S_0 \eta(E) \quad (1)$$

where S_0 is a constant to be determined for a particular BF_3 tube in the long counter. The mean flux sensitivity for a spectrum of energies characterized by a normalized distribution function $N(E)$ is given by

$$\bar{S}_L = S_0 \bar{\eta} \quad (2)$$

where

$$\bar{\eta} = \int_0^\infty \eta(E) N(E) dE \quad (3)$$

and

$$\int_0^\infty N(E) dE = 1. \quad (4)$$

⁵⁾ J. Bame, Jr., E. Haddad, J. E. Perry, Jr. and R. K. Smith, Rev. Sci. Instr. 28 (1957) 997;

J. E. Perry Jr., (December, 1957) private communication.

⁶⁾ W. D. Allen and A. T. G. Ferguson, Proc. Phys. Soc. A 70 (1957) 739.

⁷⁾ J. E. Perry, Jr. (March, 1957) private communication.

To calibrate a long counter with a radioactive neutron source the effective center of the counter must be located. A neutron detector exposed to a point source of neutrons generally has an effective center which is located at a different position than the geometrical center. This circumstance can be best explained by referring to a law discovered for the response of moderated BF_3 detectors in free-air geometry. If the distance x between the source and the detector is varied, then the counting rate $\dot{A}$ is given by the equation,

$$\dot{A} = a + \frac{b}{(x + c)^2} \quad (5)$$

where a , b , and c are constants. This equation says that the instrument acts as a point detector placed at the effective center and that room-scattered neutrons contribute a constant amount a to the counting rate. For Long Counter No. 2, which was used for the calibration of the double moderator, we find its response to a RaBe neutron source is given by

$$\dot{A} = 42 + \frac{1.830 \times 10^7}{(x + 14.2)^2}$$

where x is measured from the center of the source to the front face of the long counter. Thus, room-scattered neutrons contribute 42 c/m to the counting rate and the effective center is located 14.2 cm behind the front face.

Although published data⁶⁾ on the long counter show that c decreases with decreasing neutron energy we have employed the constant value $c = 14.2$ cm throughout this work. Furthermore, because of the effectiveness of the external shield of the long counter, the scattering term could be neglected.

In the calibration of the double moderator we assume that the effective centers coincide with the geometrical center and that the effect of room-scattered neutrons can be neglected, although the error in the latter case is larger than it is for the long counter. The measurements were performed 10 feet above the floor of an eight foot deep pit in the accelerator room to minimize the effect of room-scattered neutrons.

Fig. 4 shows the neutron spectrum (to be

discussed later) which was employed to calculate the average relative efficiency for the RaBe source. The computed average relative efficiency, $\bar{\eta} = 0.90$, and the measured flux sensitivity $\bar{S}_L = 36.0$ c/m per neutron-cm².sec for Long Counter No. 2 with RaBe neutrons yield $S_0 = 40.0$ c/m per neutron/cm².sec.

The comparison of the counts in the dosimeter,

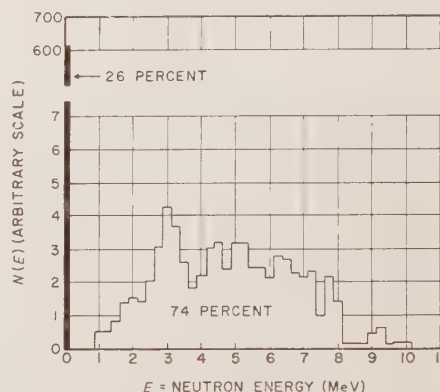


Fig. 4. RaBe neutron spectrum measured by Watson. The low-energy group was added by De Pangher to account for the result of a ratio measurement with the double moderator.

fluxmeter and long counter, dA_1 , dA_2 , and dA_L for monergic neutrons of energy E yield the flux sensitivities S_1 and S_2 for the dosimeter and fluxmeter from the equations,

$$S_1(E) = S_0 \eta(E) dA_1/dA_L \quad (6)$$

and

$$S_2(E) = S_0 \eta(E) dA_2/dA_L. \quad (7)$$

Let us also define the ratio of counts for monergic neutrons

$$r = S_1/S_2. \quad (8)$$

For neutrons of an extended energy range we measure the average quantities,

$$\bar{S}_1 = S_0 \bar{\eta} A_1/A_L \quad (9)$$

$$S_2 = S_0 \bar{\eta} A_2/A_L \quad (10)$$

and

$$R = \bar{S}_1/\bar{S}_2. \quad (11)$$

Figs. 5 and 6 show the experimental data obtained for S_1 and S_2 with monergic neutrons for $\bar{S}_1$ and $\bar{S}_2$ with neutrons from several radioactive sources. In evaluating the data obtained with the radioactive neutron sources the

average relative efficiencies of the long counter were calculated from the neutron energy spectra involved. The average energies of these sources

and the corresponding average relative efficiencies of the long counter are listed in table 1.

The dose sensitivity of the dosimeter was

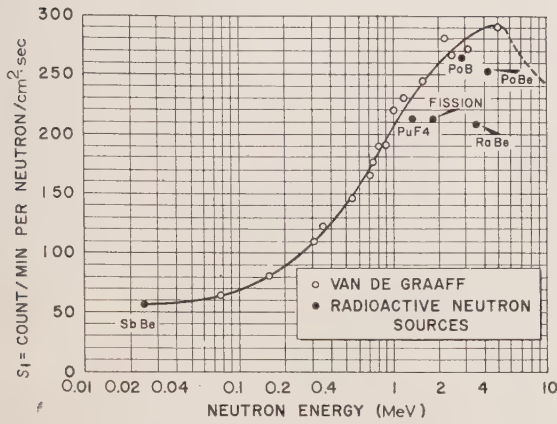


Fig. 5. Flux sensitivity S_1 of the dosimeter.

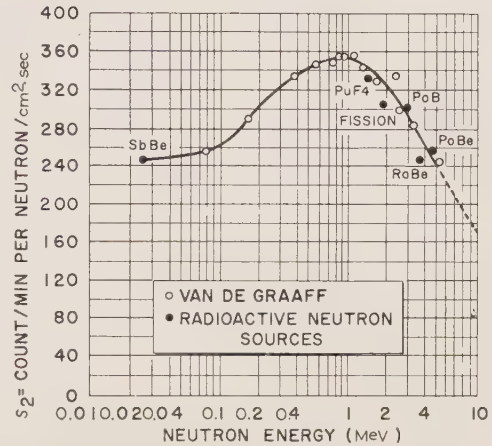


Fig. 6. Flux sensitivity S_2 of the fluxmeter.

TABLE 1

Average energies and average relative efficiencies of the long counter for radioactive neutron sources

Source	Average Energy (MeV)	Average Relative Efficiency	Remarks on Spectrum
PuF ₄	1.4	0.99	Assume spectrum same as the spectrum calculated for a PoF source by Hess ¹⁴⁾
Spontaneous Fission of Pu ²⁴⁰	1.9	0.97	Assume spectrum same as the fission neutron spectrum of U ²³⁵ measured by Cranberg, Fryer, Neresen and Rosen ¹⁵⁾
PoB	2.8	0.96	Measured by Watson ¹⁶⁾
RaBe	3.6	0.90	Measured by Watson ¹⁶⁾ and modified by De Pangher ⁴⁾
PoBe	4.3	0.92	Measured by Whitmore and Baker ¹⁸⁾

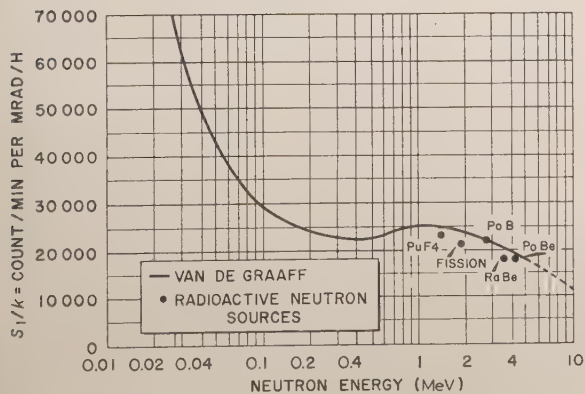


Fig. 7. Sensitivity of dosimeter S_1/k for single-collision theory absorbed dose.

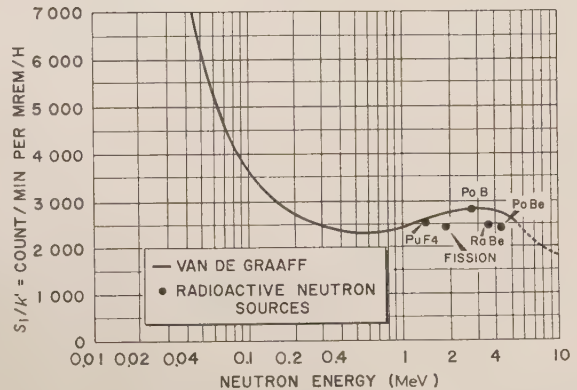


Fig. 8. Sensitivity of dosimeter S_1/k' for single-collision theory RBE dose.

calculated in four different ways from S_1 for monergic neutrons and from $\bar{S}_1$ for neutrons from radioactive sources. This information is

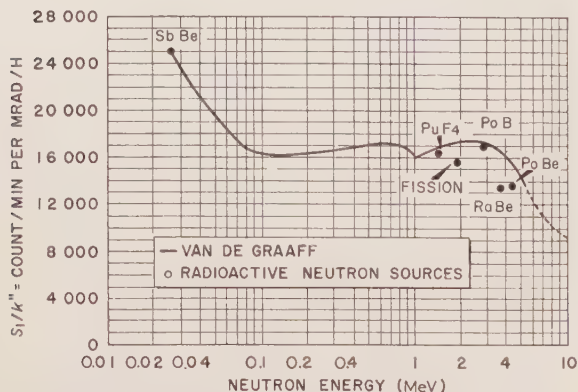


Fig. 9. Sensitivity of dosimeter S_1/k' for multiple-collision theory absorbed dose.

presented in figs. 7 through 10 and in table 2. The flux-to-dose conversion factors k , k' , k'' , and k''' applied in these cases give single-collision theory absorbed dose⁸), single-collision RBE dose⁹), multiple-collision theory absorbed dose¹⁰) and multiple-collision theory RBE dose¹⁰), respectively. The choice of the theory depends on the experimental situation involved and is left to the reader to make.

Fig. 11 shows the results of the measurements of the angular response of the dosimeter for a RaBe neutron source. The response for this particular source at $\theta = 0^\circ$ is about 12 per cent lower than it is at $\theta = 90^\circ$. Preliminary measurements on a PuF_4 neutron source indicate an increase of about 8 per cent in the response at 0° over the response at 90° . Measurements taken on the shorter, insensitive (see Introduction) BF_3 tube and the present sensitive BF_3 tube show that the length of the sensitive region of the sensitive tube shown in fig. 2 is just about optimum for achieving the best uniform angular response in the dosimeter. (Care must be taken to center the sensitive tube inside the dosimeter;

otherwise an asymmetrical angular response results.)

W. G. Spear and L. V. Zuerner of this labor-

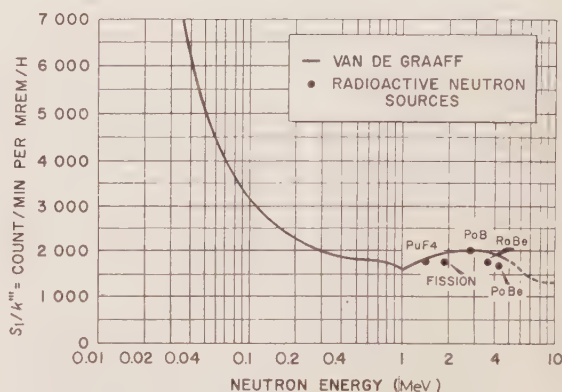


Fig. 10. Sensitivity of dosimeter S_1/k''' for multiple-collision theory RBE dose.

atory recently tested a spherical dosimeter consisting of a 10-inch diameter paraffin sphere and a boron-ZnS detector at its center. They found very uniform angular response in spite of the 2.5-inch cylindrical hole cut in the moderator to admit an R.C.A. type 6655 photomultiplier. It appeared that the diameter of the sphere was not optimum for use as a dosimeter, however, because its response was slightly inferior to the

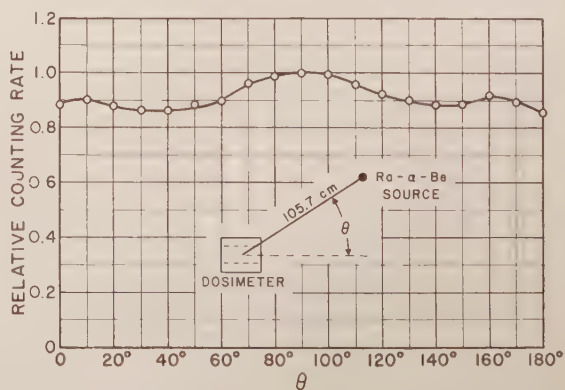


Fig. 11. Angular response of dosimeter to RaBe neutrons.

response of the double moderator dosimeter. Probably, a small increase in the diameter of the sphere would improve its response. The weight of the spherical dosimeter including the transistorized detection equipment was about 24 pounds.

⁸) W. C. Roesch, Neutron Measurements (I), HW-32476 (July, 1954).

⁹) National Bureau of Standards Handbook 63 (1957) 15.

¹⁰) National Bureau of Standards Handbook 63 (1957) 64.

TABLE 2

Dose and flux sensitivities of the double moderator for monergic neutrons and for neutrons from radioactive sources

Radio- active $\uparrow$ Neutron Sources	$E(\text{MeV})$	S_1	S_2	S_1/S_2	$100 k$	$100 k'$	$100 k''$	$100 k'''$	S_1/k	S_1/k'	S_1/k''	S_1/k'''
	0.025	55	247	0.224	0.077	0.42	0.219	0.54	71 400	13 100	25 100	10 200
	0.03	56	248	0.226	0.090	0.51	0.237	0.66	62 200	10 900	23 600	8 520
	0.04	58	250	0.230	0.115	0.73	0.275	0.91	50 400	8 000	21 100	6 400
	0.05	58	251	0.233	0.137	0.92	0.30	1.10	42 300	6 320	19 500	5 270
	0.06	60	253	0.237	0.158	1.11	0.33	1.34	38 000	5 410	18 200	4 480
	0.07	61	255	0.241	0.178	1.30	0.35	1.55	34 300	4 690	17 400	3 930
	0.08	63	257	0.244	0.197	1.50	0.38	1.76	32 000	4 200	16 700	3 570
	0.09	65	259	0.248	0.214	1.67	0.40	1.99	29 900	3 830	16 300	3 270
	0.10	66	261	0.252	0.231	1.85	0.41	2.16	28 600	3 570	16 100	3 060
	0.15	77	285	0.270	0.30	2.60	0.48	3.0	25 700	2 960	16 200	2 540
	0.20	88	304	0.288	0.37	3.3	0.54	3.9	24 100	2 730	16 200	2 250
	0.25	98	319	0.307	0.42	3.8	0.60	4.6	23 300	2 560	16 400	2 130
	0.30	107	328	0.325	0.47	4.4	0.65	5.4	22 800	2 440	16 500	2 000
	0.40	123	341	0.361	0.55	5.3	0.74	6.6	22 400	2 300	16 700	1 870
	0.50	139	348	0.398	0.62	6.1	0.82	7.6	22 400	2 270	17 000	1 830
	0.60	153	351	0.435	0.67	6.7	0.89	8.4	22 900	2 270	17 100	1 820
	0.70	167	355	0.471	0.71	7.2	0.97	9.3	23 500	2 300	17 200	1 800
	0.80	181	356	0.508	0.76	7.8	1.06	10.3	23 800	2 310	17 100	1 760
	0.90	194	357	0.544	0.80	8.3	1.15	11.6	24 400	2 330	16 800	1 670
	1.00	207	356	0.581	0.84	8.7	1.31	12.7	24 700	2 370	15 800	1 630
	1	207	356	0.581	0.84	8.7	1.31	12.7	24 700	2 370	15 800	1 630
	1.5	243	341	0.712	0.99	9.3	1.43	13.0	24 300	2 590	17 000	1 870
	2	259	322	0.804	1.12	9.6	1.49	13.1	23 300	2 680	17 400	1 980
	2.5	268	303	0.884	1.21	9.8	1.54	13.3	22 200	2 740	17 400	2 020
	3	274	287	0.956	1.30	10.0	1.59	13.5	21 100	2 750	17 200	2 030
	4	288	266	1.081	1.46	10.6	1.79	14.6	19 700	2 720	16 100	1 970
	5	292	248	1.173	1.62	11.2	2.01	16.0	18 000	2 600	14 500	1 830
	6	276	219	1.260	1.71	11.8	2.24	17.6	16 200	2 330	12 300	1 570
	7	263	200	1.312	1.89	12.6	2.39	19.3	14 700	2 080	11 000	1 360
	8	256	188	1.366	1.90	13.1	2.57	19.4	13 500	1 960	10 000	1 320
	9	251	178	1.407	2.00	13.4	2.64	19.0	12 500	1 870	9 500	1 320
	10	244	170	1.434	2.07	13.5	2.65	18.1	11 800	1 810	2 200	1 280
PuF ₄	1.4	214	336	0.636	0.93	8.6	1.30	11.8	23 000	2 490	16 500	1 810
Fission	1.9	214	307	0.696	1.01	8.7	1.36	11.9	21 200	2 460	15 700	1 800
PoB	2.8	276	301	0.916	1.26	10.0	1.61	13.6	21 900	2 760	17 100	2 030
RaBe	3.6	208	249	0.836	1.17	8.5	1.55	11.7	17 800	2 450	13 400	1 780
PoBe	4.3	254	258	0.986	1.44	10.7	1.86	15.0	17 600	2 370	13 700	1 690
PuBe	4.5	260	259	1.005	1.46	10.8	1.90	15.3	17 800	2 410	13 700	1 700

 S_1 = Count/min per neutron/cm²·sec for dosimeter. S_2 = Count/min per neutron/cm²·sec for fluxmeter. S_1/k = Count/min per mrad/h from first-collision theory. S_1/k' = Count/min per mrem/h from first-collision theory. S_1/k'' = Count/min per mrad/h from multiple-collision theory. S_1/k''' = Count/min per mrem/h from multiple-collision theory. $\uparrow$ Except for the PuBe neutron source the average flux sensitivities are measured quantities. However, the average flux-to-dose conversion factors are quantities calculated from the neutron-energy spectra.

4. Average Energy Measurements

Fig. 12 shows a plot of $r = S_1/S_2$ for monoenergetic neutrons of energy E . For an extended energy spectrum let us define the average energy $\bar{E}$ from the equation

$$\bar{E} = \int_0^\infty EN(E) dE \quad (12)$$

and inquire what conditions must be met for the approximate equality of E and E' where E' is the neutron energy evaluated at $r = R$ from the plot in fig. 12 (R is the experimentally observed ratio of counts). From eqs. (9) through (11) we learned how to measure $\bar{S}_1$, $\bar{S}_2$, and R and now we present alternative equations for the calculation of these quantities; namely,

$$\bar{S}_1 = \int_0^\infty S_1(E)N(E) dE \quad (13)$$

$$\bar{S}_2 = \int_0^\infty S_2(E)N(E) dE \quad (14)$$

and

$$R = \frac{\int_0^\infty r S_2 N dE}{\int_0^\infty S_2 N dE} \quad (15)$$

Until we have some knowledge of $N(E)$ we cannot compare $\bar{E}$ and $\bar{E}'$. Let us, therefore, assume a uniform spectrum of mean energy $\bar{E}$ and calculate $\bar{S}_1$, $\bar{S}_2$, and R for this spectrum. The results of the calculations are presented in table 3. A plot of the error

$$e = 100 \frac{E' - \bar{E}}{\bar{E}} \quad (16)$$

given in fig. 13 for the condition of a uniform spectrum, illustrates the accuracy of measuring average neutron energies with the double moderator.

Let us apply the information contained in table 3 to estimate the error in measuring the average energy of neutrons emerging at 0° from a thick titanium-deuteride target bombarded by 2-MeV deuterons on the assumption that this spectrum is uniform between the limits 2 MeV and 5 MeV. It can be easily shown that for a uniform spectrum extending from E_1 to E_2 that

$$R(E_1, E_2) = \frac{E_2 \bar{S}_1(E_2) - E_1 \bar{S}_1(E_1)}{E_2 \bar{S}_2(E_2) - E_1 \bar{S}_2(E_1)} \quad (17)$$

and for the case under consideration we get $R = 1.003$. We find that the result $E' = 3.39$ MeV is in good agreement with the average $\bar{E} = 3.50$ MeV.

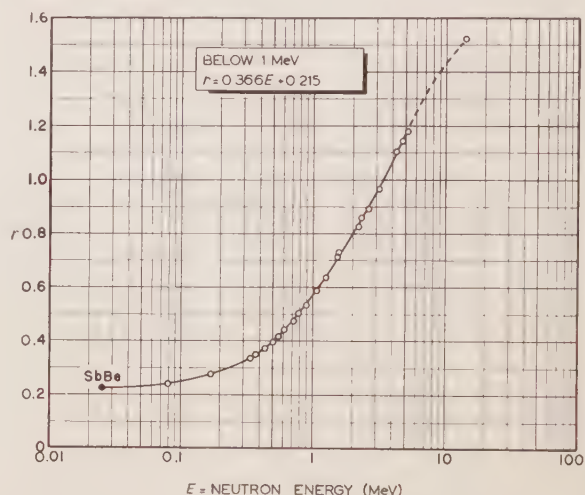


Fig. 12. Ratio $r = S_1/S_2$ versus neutron energy E .

TABLE 3

Calculated response of double moderator for uniform neutron energy spectrum extending up to energy $2\bar{E}$

$2\bar{E}$ (MeV)	$\bar{S}_1$	$\bar{S}_2$	R
0	55.0	244.0	0.225
1	134.8	331.1	0.407
2	187.3	336.0	0.558
3	214.1	325.2	0.658
4	230.6	312.8	0.737
5	242.9	301.8	0.805
6	249.8	290.5	0.860
7	252.6	278.9	0.906
8	253.4	268.2	0.945
9	253.4	258.8	0.979
10	252.8	250.3	1.010
11	251.6	242.6	1.037

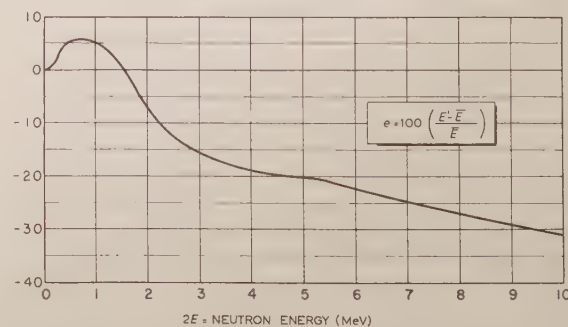


Fig. 13. Error in measuring average neutron energy for uniform spectrum with the double moderator.

Fig. 14 shows the result of average energy measurements performed on neutrons emitted at 0° from the $D(d,n)He^3$ reaction in a thick titanium-deuteride target for deuteron energies up to 2 MeV. The average energy represented by the dashed curve was calculated from the 0° differential cross section data¹¹⁾ and from the stopping power¹²⁾ of the target with the assumption of one deuterium atom per two titanium

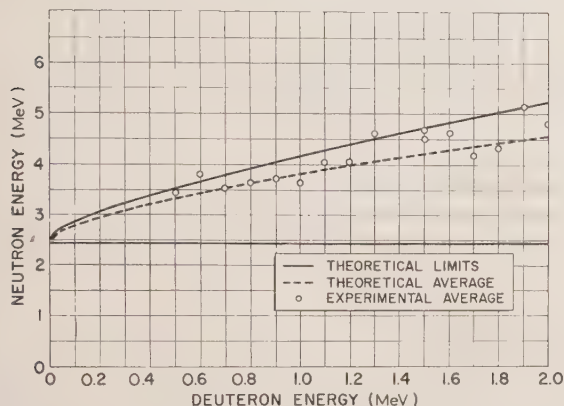


Fig. 14. Average energy measurements on neutrons produced in the $D(d,n)He^3$ reaction in a thick titanium-deuteride target at angle of 0° .

atoms in the target and for a uniform dispersion of the deuterium in the titanium. The agreement between theory and experiment is satisfactory. Some of the scatter in the data could be traced to lack of reproducibility in the neutron yield per unit integrated target current.

Below 1 MeV, an argument is now presented to show that the double moderator measures average neutron energy without the assumption of a uniform energy spectrum. From fig. 12 the data below 1 MeV fit a straight line whose equation is

$$r = 0.366 E + 0.215. \quad (16)$$

By averaging r over an arbitrary spectrum whose upper bound is 1 MeV and rearranging the equation we find

$$\bar{E} = \frac{\bar{r} - 0.215}{0.366} \quad (17)$$

and for comparison, by definition, we have

$$E' = \frac{R - 0.215}{0.366}. \quad (18)$$

After noting that the quantity S_2 in eq. (15) is reasonably uniform below 1 MeV we can make the following approximation:

$$R \cong \bar{r}; \quad (19)$$

consequently, we have $E' \cong \bar{E}$.

Experimentally we can test the assertion just made by making average energy measurements on neutrons generated in the $T(p,n)He^3$ reaction in a thick titanium-tritide target. Fig. 15 shows

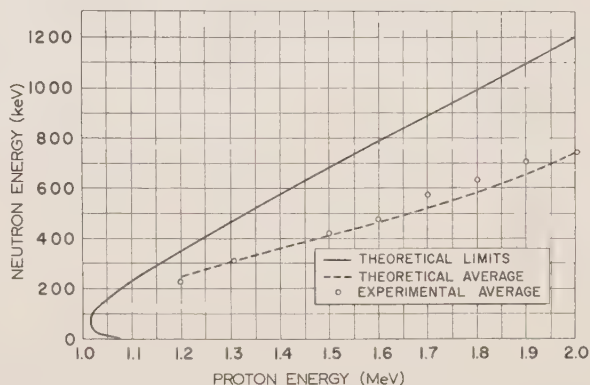


Fig. 15. Average energy measurements on neutrons produced in the $T(p,n)He^3$ reaction in a thick titanium-tritide target at angle of 0° .

agreement between theory and experiment to within 10 per cent for various proton bombarding energies up to 2 MeV. The dotted curve was calculated from the 0° differential cross section data¹³⁾ and from the stopping power of the target by the same method employed for the $D(d,n)He^3$ reaction discussed previously.

5. Checks on Neutron Energy Spectra

A neutron energy spectrum characterized by the distribution function $N(E)$ may be checked by testing the equality of the last two members of the following equation

$$R = \frac{\int_0^\infty S_1(E)N(E) dE}{\int_0^\infty S_2(E)N(E) dE} = A_1/A_2 \quad (20)$$

¹¹⁾ G. T. Hunter and H. T. Richards, Phys. Rev. **76** (1949) 1445.

¹²⁾ S. K. Allison and S. D. Warshaw, Revs. Mod. Phys. **25** (1953) 779.

¹³⁾ G. A. Jarvis, A. Hemmendinger, H. V. Argo and R. F. Taschek, Phys. Rev. **79** (1950) 929.

a result obtained by combining eqs. (9), (10), (13), and (14).

This method was used to check neutron energy spectra from the following radioactive neutron sources: a PuF_4 source, a spontaneous Pu^{240} fission source, a PoB source, a RaBe source, and a PoBe source. The method is currently being used to study the neutrons

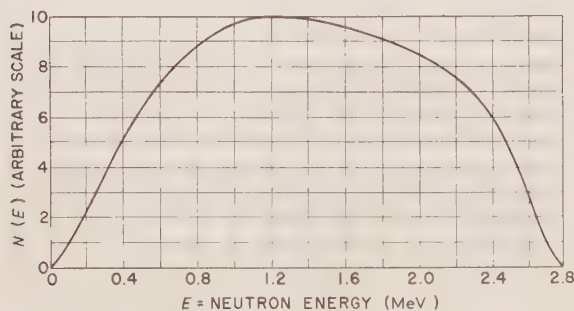


Fig. 16. PoF neutron spectrum calculated by Hess.

produced in the $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$ reaction for different excited states of the residual nucleus B^{10} .

Hess¹⁴) employing simple theoretical assumptions, has calculated the neutron energy spectrum for a PoF source. It is shown in fig. 16. A PuF_4 neutron source was constructed and measured with the double moderator with the

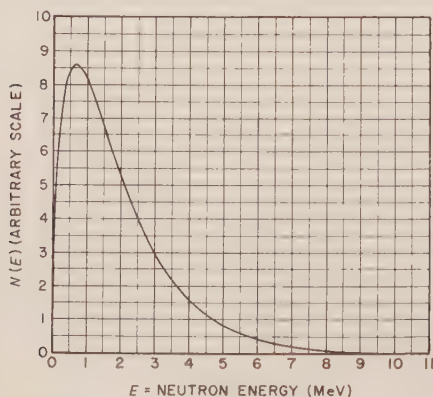


Fig. 17. Fission neutron spectrum of U^{235} from empirical formula $N(E) = kE^{\frac{1}{2}} \exp(-0.775 E)$. Given by Cranberg, Frye, Neresen and Rosen.

expectation that its energy spectrum would be similar to the energy spectrum for a PoF neutron source.

The spectrum shown in fig. 17 was calculated

from an empirical formula¹⁵) given by Cranberg, Frye, Neresen, and Rosen for the fission neutron spectrum of U^{235} . Their measurements were performed by the time-of-flight method. The double moderator was exposed to neutrons from the spontaneous fission of Pu^{240} with the assumption

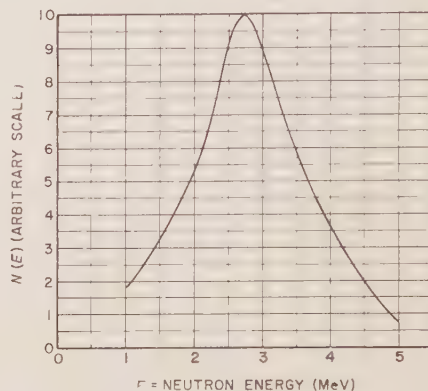


Fig. 18. PoB neutron spectrum by Watson.

that the neutron energy spectrum would be similar to the fission neutron energy spectrum for U^{235} .

Fig. 18 shows the neutron spectrum¹⁶) obtained by Watson with nuclear track plates for a PoB neutron source. The same source, though decayed by 13 half-lives, was studied with the double moderator.

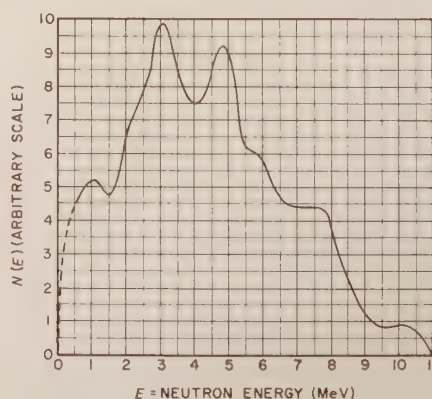


Fig. 19. PoBe neutron spectrum by Whitmore and Baker.

¹⁴) W. N. Hess, University of California Radiation Laboratory Report, UCRL-3829 (July, 1957) unpublished.

¹⁵) L. Cranberg, G. Fryer, N. Neresen and L. Rosen, Phys. Rev. **103** (1956) 662.

¹⁶) E. C. Watson, General Electric Company, Hanford Laboratories Operation (private communication on work done in 1951).

Neutrons from a RaBe source surrounded by several inches of lead were measured by Watson with nuclear track plates. The neutron energy spectrum¹⁶⁾ obtained by Watson was modified⁴⁾ by De Pangher as shown in fig. 4 to give results consistent with the double moderator. The low-energy neutrons¹⁷⁾ are thought to be produced by the $\text{Be}^9(\alpha, n)^3\text{He}^4$ reaction. The same RaBe source used by Watson was also used by De Pangher.

The PoBe neutron spectrum¹⁸⁾ obtained by Whitmore and Baker is shown in fig. 19. The low-energy, dotted part of the curve was added to give results consistent with the double moderator. It should be noted that the low-energy portion of the RaBe spectrum is considerably larger than it is in the PoBe spectrum.

The results of the measurements of R obtained with the double moderator on these radioactive neutron sources are tabulated in table 4 along with the calculated values. The agreement is considered satisfactory in all cases within the limits of error imposed by the measurements of R and the accuracy with which the relative efficiency of Long Counter No. 2 is known.

TABLE 4

Checks on neutron energy spectra from radioactive sources

Source	R (measured)	R (calculated)
PuF ₄	0.636	0.656
Spontaneous fission of Pu ²⁴⁰	0.696	0.700
PoB	0.916	0.906
RaBe	0.836	0.871
PoBe	0.986	0.992

6. Effective Center and Response to Room-Scattered Neutrons

The method for locating the effective center of a moderated BF₃ detector and for measuring its response to room-scattered neutrons makes use of eq. (5) in one of the two forms:

$$z = at + b \quad (21)$$

where

$$z = (x + c)^2 \dot{A} \quad \text{and} \quad t = (x + c)^2 \quad \text{or} \quad (\dot{A} - a)^{-\frac{1}{2}} = b^{-\frac{1}{2}}(x + c). \quad (22)$$

Data are obtained on the counting rate $\dot{A}$ as a function of the distance x between the center of a neutron source and a convenient reference point on the detector. For the long counter the reference point was taken to be the center of the front face, while for the dosimeter and the fluxmeter it was taken as the geometrical center. The first step in the analysis of the data is to find a , which gives the response to room-scattered neutrons. Several values of c are selected in intervals of 0.5 cm about the expected value to give the best straight line plot of z versus t . Until the right choice is made the data make a poor fit to a straight line. Some irregularities in the data occur for small values of x , because of the finite size of the detector. For example, values for x less than 60 cm should be ignored in making the fit to eq. (21) to find a . A least analysis of the data at this point does not appear profitable because it is time consuming and does not yield better results than can be obtained from visual inspection. With this measurement of a the quantity $(\dot{A} - a)^{-\frac{1}{2}}$ is calculated as a function of x and eq. (22) is fitted by least-squares analysis to give the final values of b and c . Figs. 20 and 21 show the fit of the experimental data to eqs. (21) and (22) for Long Counter No. 2 to a RaBe neutron source.

The results of the measurements of a , b , and c for the dosimeter, fluxmeter, and Long Counter No. 2 are tabulated in table 5 for various neutron sources. For the double moderator these data

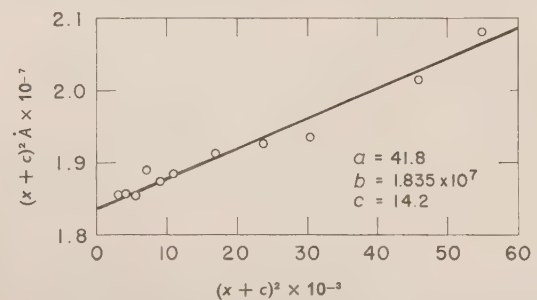


Fig. 20. Fit of data on Long Counter No. 2 for RaBe neutrons to eq. (21) in text.

¹⁷⁾ W. R. Dixon, A. Bielisch and K. W. Geiger, Can. Jour. Phys. 6 (1957) 699.

¹⁸⁾ B. G. Whitmore and W. B. Baker, Phys. Rev. 78 (1950) 799.

TABLE 5
Properties of the double moderator and Long Counter No. 2 for various neutron sources

Instrument	Neutron Source	Average Energy (MeV)	a ($\frac{\text{Count}}{\text{min}}$)	b ($\frac{\text{Count-cm}^2}{\text{min}}$)	c (cm)	ϵ %	R	R'	R''
fluxmeter	SbB	0.025	285	2.94×10^7	— 1.0	8.7	0.239	0.224	0.222
dosimeter			114	6.53×10^6	— 1.5	14.5			
fluxmeter	T(p,n)He ³	0.916	1680	2.86×10^8	— 0.5	5.5	0.550	0.563	0.557
dosimeter			745	1.592×10^8	— 1.0	4.4			
fluxmeter	RaBe	3.6	1161	1.336×10^8	— 0.5	7.9	0.836	0.854	0.845
dosimeter			611	1.129×10^8	— 1.0	5.0			
fluxmeter	PoBe	4.3	95	8.27×10^6	0.0	10.3	0.986	1.007	0.988
dosimeter			70	8.17×10^6	— 1.0	7.7			
Long Counter	RaBe	3.6	42	1.830×10^7	14.2	2.2			

show that the effective centers are slightly displaced away from the geometrical center toward the neutron source. The quantity

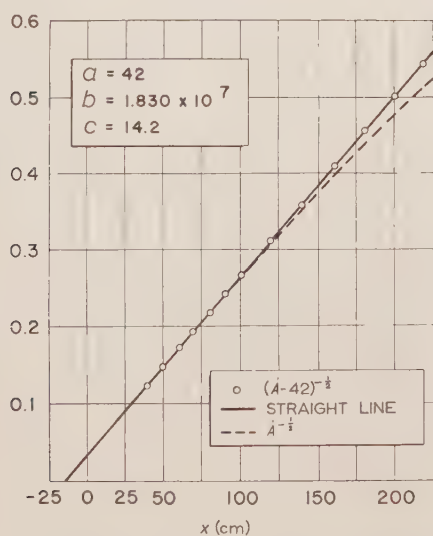


Fig. 21. Fit of data on Long Counter No. 2 for RaBe neutrons to eq. (22) in text.

$\epsilon = 100 a/A$ is a measure of the response of the detectors to room-scattered neutrons compared to the response to direct neutrons when the effective centers of the detectors are located at a distance of 100 cm from the neutron source. The entries in the three last columns will be discussed in the following section.

7. Errors in the Measurement of R

Because all the data presented for R in this paper are based on no fewer than 10 000 counts the standard statistical errors do not exceed two per cent. To study the effect of room-scattered neutrons on these results and also the effect of assuming that the effective center coincides with the geometrical center for the dosimeter and for the fluxmeter, let us define the following quantities:

$$R = \dot{A}_1/\dot{A}_2 = \frac{a_1 + b_1(x + c_1)^{-2}}{a_2 + b_2(x + c_2)^{-2}} \quad (23)$$

$$R' = \frac{\dot{A}_1 - a_1}{\dot{A}_2 - a_2} = \frac{b_1/b_2}{x + c_1} \quad (24)$$

and

$$R'' = b_1/b_2. \quad (25)$$

The first definition given by eq. (23) defines a quantity which generally decreases with increasing x and was the definition employed for the data presented in this paper. The second definition given by eq. (24) is corrected for the effect of room-scattered neutrons but still is dependent on x because the effective center does not coincide with the geometrical center. The third definition given by eq. (25) defines a quantity which is independent of x and, presumably, it is the best definition. For the data presented in this paper a compromise

between the two effects and the counting rate desired was intuitively sought by measuring R according to eq. (23) for values of x in the range 80–100 cm. It is evident that the procedure which was outlined in the previous section for measuring the constants in eqs. (24) and (25) is rather laborious, and, consequently, it was only used in the few cases tabulated in the last two columns of table 5 to estimate the errors in taking measurement at $x + c = 100$ cm. Except for SbBe neutrons the maximum difference in the results amounts to about two per cent. It appears, therefore, that the standard error in measuring R did not exceed three per cent except for very low neutron energies where the error was about eight per cent. A study, now in progress, of the neutrons from the $\text{Be}^9(d,n)\text{B}^{10}$ with the Van de Graaff accelerator shows that $x = 90$ cm is the optimum distance for obtaining good agreement between values of R and R'' .

8. Sources of Error

The main sources of error in the calibration of the double moderator lie in the uncertainty in the knowledge of the energy sensitivity of Long Counter No. 2.

The RaBe neutron source which was used to calibrate it had been calibrated at the National Bureau of Standards to an absolute accuracy of about $\pm$ three per cent. The average relative efficiency of Long Counter No. 2 for RaBe neutrons was taken to be 0.90 ± 0.02 . If we ignore sources of error other than the two listed we might estimate an error of about $\pm$ four per cent in the use of Long Counter No. 2. Unfortunately, we cannot assume that the relative efficiency of Long Counter No. 2 is the same as the Harwell Long Counter⁶⁾ or the Los Alamos Long Counter⁵⁾. In fact, we are not even certain that the Harwell and Los Alamos counters agree. It is the experience of this writer that the density of paraffin varies as much as five per cent from one pouring to the next. The configuration of the cadmium shielding in the Harwell counter certainly differs from the arrangements employed at Los Alamos and Hanford. Although two counters Long Counter

No. 1 and Long Counter No. 2 which were constructed at Hanford agree¹⁹⁾ quite well with each other, the effective center for RaBe neutrons of Long Counter No. 2 is displaced 3 cm further away from the front face than is the effective center of the Harwell counter. It would be desirable to construct long counters from the same machine drawings out of polyethylene instead of paraffin and cross-check them in various laboratories to improve the accuracy of neutron measurements. Considering the various factors it is estimated that the measurements of dose or flux with Long Counter No. 2 should not exceed 10 per cent.

9. Discussion

The use and calibration of a particular moderated BF_3 detector for measuring fast neutron flux, dose and average energy has been described. Although the instrument is heavy and has a directional response, it is an excellent dosimeter in the energy range 0.1 to 5.0 MeV for it is very sensitive to neutron radiation and quite insensitive to gamma radiation. For field use, the filling of the BF_3 tube has been changed from 25 cm Hg pressure of enriched BF_3 gas to a mixture consisting of 20 cm Hg pressure of argon gas and 5 cm Hg pressure of enriched BF_3 gas to reduce the operating voltage and the sensitivity. (The constitution of enriched BF_3 gas is 96 per cent B^{10} and 4 per cent B^{11} .) A lightweight battery BF_3 count-rate meter is being used with it. It has been used for measuring dose rates and in shielding studies. A spherical version of this detector should result in weight reduction and in improved angular response. Unlike other dosimeters such as the Hurst dosimeter it overestimates the dose from low-energy neutrons rather than underestimating it. This arrangement has possibilities for use as a monitor in a disaster situation if the BF_3 tube is replaced by foils which become radioactive upon capture of the thermalized neutrons.

¹⁹⁾ J. De Pangher, General Electric Company, Hanford Laboratories Operation Report, HW-56199 (May, 1958) unpublished.

Acknowledgments

I wish to extend my thanks to Dr. W. C. Roesch for initiating the study of moderated BF_3 detectors as instruments for measuring neutron dose, to Mr. M. L. Leibel for the operation of the Van de Graaff accelerator and for taking many of the measurements, to Dr. D. C. Wood for supplying the PoBe and SbBe

neutron sources and for furnishing the information that his moderator was only half as sensitive as mine because of the steel instead of aluminum, to Mr. R. E. Slater for providing the Pu^{240} source and the PuF_4 source, and to Mr. L. J. Defferding for building and testing several double moderators to check the reproducibility in construction.

A CURRENT INTEGRATOR WITH DIGITAL OUTPUT

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Received 25 May 1959

This note contains a proposal to integrate currents larger than $1 \mu\text{A}$ by utilizing their magnetizing action. The proposed method eliminates the usual integrating capacitor

with the associated leakage and soakage problems and gives the value of the collected charge in digital form.

The current i , which is to be integrated, passes through one of two coils wound on a piece of ferromagnetic material. The permeability, μ , of this material depends on the field H_i caused by the current i . The other coil forms the self-inductance L of an LC -circuit of an oscillator. The self-inductance L and therefore the frequency ω of the oscillator depend on μ and thus on i . It may be advantageous to introduce a premagnetization of the ferromagnetic material in order to optimize the dependence of ω on i .

The frequency ω of the oscillator is determined by comparing it to a second identical oscillator, which is independent of the current i , and which has a fixed frequency ω_0 . This frequency ω_0 is the frequency of the first oscillator, when $i = 0$. This method has the advantage that, when $i \neq 0$, the frequency shift $\Delta\omega$, which is the beat frequency between the two oscillators, can be measured in a mixing stage. It also has the advantage that frequency changes due to other causes (temperature-variations, stray fields, change of premagnetization, etc.) tend to cancel in the measurement. The separate beats can be counted on a scaler after voltage-amplification and pulse-shaping. The total number of beats N is then related to the measured charge q . A block-diagram of the scheme is given in fig. 1.

The dependence of N on q can be expressed by the following relation

$$N_t = \int_0^t \Delta\omega(\tau) d\tau = \int_0^t \frac{d\omega}{di} i(\tau) d\tau \quad (1)$$

N_t is the number of the beats counted during

the time t , $\Delta\omega(\tau)$ and $i(\tau)$ are the beat frequency and the current at the time τ .

It can easily be shown, that

$$\frac{d\omega}{di} = -\frac{\omega_0}{2H_0} \left(\frac{d\mu/\mu}{dH/H} \right)_{H_0} \frac{0.4 \pi m}{l} \quad (2)$$

under the assumptions, that H_i is parallel to H_0 , and then $dH_i = dH_0 = dH$. H_0 is the premagnetization field, μ the permeability of the ferromagnetic material, m the number of turns of the coil, through which the current i passes and l the length of the magnetic circuit.

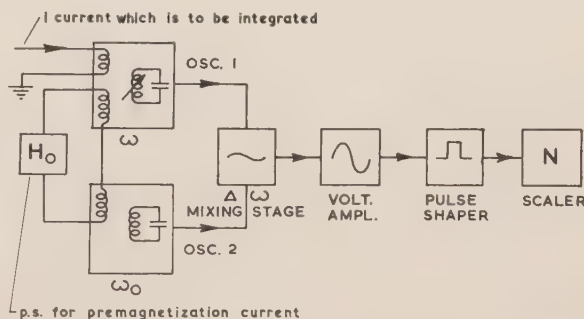


Fig. 1. Blockdiagram of the integrator.

$((d\mu/\mu)/(dH/H))_{H_0}$ can be supposed to be nearly constant in a small region around a suitable chosen premagnetization field H_0 .

In that case $d\omega/di$ is constant and can be taken outside the integral sign in eq. (1). This equation then takes the form

$$N_t = \frac{d\omega}{di} \int_0^t i(\tau) d\tau = -\frac{\omega_0}{2H_0} \left(\frac{d\mu/\mu}{dH/H} \right)_{H_0} \frac{0.4 \pi m}{l} q_t \quad (3)$$

which shows that under certain conditions N is

proportional to q . $((d\mu/\mu)/(dH/H))H_0$ is intrinsically negative. It should be noted that μ is the so-called reversible permeability, defined by

$$\mu_{\text{rev}} = \left(\lim_{\Delta H \rightarrow 0} \frac{\Delta B}{\Delta H} \right)_{H_0}.$$

This is the permeability, which gives the relation between the variation of the induction ΔB and an alternating field ΔH , which causes the variation ΔB and which is superimposed on a fixed, premagnetizing field H_0 . ΔH is the field H_ω caused by the oscillator circuit. μ_{rev} depends on the premagnetization H_0 , while the variation of μ_{rev} is caused by H_i , which can either increase or decrease H_0 , if H_i is in the same direction as H_0 respectively in the opposite direction of H_0 .

In the case of interest here a ferromagnetic material was desired, which had a large and constant $d\mu/dH$ for a certain premagnetization H_0 in a small region around H_0 . Also of importance was the dependence of the quality $Q = \omega/\Delta\omega'$, on the nature of the ferromagnetic material. Q is a measure of the natural uncertainty $\Delta\omega'$ in frequency of the oscillator. This uncertainty $\Delta\omega'$ is the source of spurious counts.

It was found that Ferroxcube IIIA¹⁾ had a large and constant $d\mu/dH$ over a finite range of premagnetization and had a Q of the order of 10^5 , if the frequencies were restricted to be below 50 kc/s. The counting rate of spurious beats $\Delta\omega$ for the combination of the two oscillators is then of the order of $2\Delta\omega' = 2\omega/Q = 1$ c/s, if all other parameters which influence Q can be suppressed.

Because of the requirement of a high Q , great care was taken to avoid parasitic coupling. The geometry of the coils and magnetic circuits can be seen in fig. 2.

By splitting the oscillator coil into two equal sections wound on the side legs of a ferroxcube frame, it was possible to make the ac-field zero in the middle leg, where the dc-coils are located, and thus no coupling could occur. The magnetic flux of the dc-coils, however, is distributed equally over both side legs. The premagnetization field H_0 could be obtained by a current

through one of the coils on the middle leg, since no hysteresis effects were observed by changing this current. A permanent magnet could be used instead of a dc-coil, but it would be difficult to place in the system. The other coil on the middle leg carries the current i , which is to be integrated. The field H_i is made opposite to H_0 and thus the net field and the frequency of the oscillator decrease.

Other parameters which influence Q are e.g. the temperature dependence of tube capacitances in the oscillator circuit which take part in determining the frequency. The importance of these effects can be minimized by using a Clapp-type oscillator²⁾. Other temperature effects and stray fields may also give spurious counts.

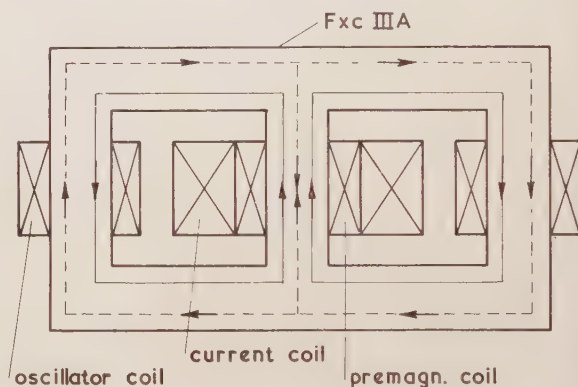


Fig. 2. The magnetic circuit of oscillator 1. The solid line shows the direction of the flux caused by the current i and the premagnetization current. The dashed line shows the direction of the flux caused by the oscillator coil. (Fxc = ferroxcube).

In order to avoid these counts both oscillators should be identical and placed in a temperature controlled, shielded box. Preliminary experiments indicate that it is possible to reach a level of spurious counts as low as 1 c/s. In that case it is possible to integrate currents, which make $\Delta\omega = 1000$ c/s, with an accuracy of 0.1%.

In an application here two oscillators were used, which have a frequency of 37.8 kc/s without premagnetization. Fig. 3 shows the

¹⁾ Data sheet EP9201, Philips' factories, Eindhoven, Holland.

²⁾ W. A. Edson, Vacuum Tube Oscillators (Wiley, New York, 1953).

dependence of the frequency on the premagnetization field H_0 . No hysteresis effects were observed. For this reason it is possible to use the same figure to show the dependence of $\Delta\omega$ on the field H_i superimposed on H_0 . In the exper-

beam of a synchrocyclotron. The proposed system was found to be inadequate because of lack of sensitivity, since in many scattering experiments beam currents as low as about $1 \text{ m}\mu\text{A}$ are used.

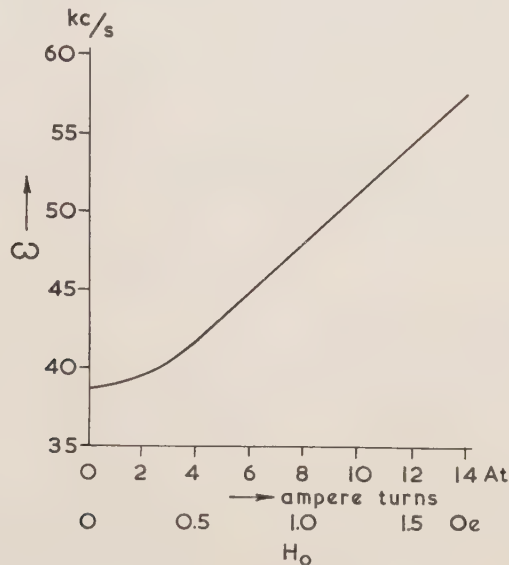


Fig. 3. The dependence of the frequency ω on the premagnetization field H_0 . The dependence of $\Delta\omega$ on i can be found as the dependence of ωH^8 in ampere turns around any point H_0 , at which the frequency ω_0 is chosen for $i = 0$. Therefore the scale is also given in ampere turns. One ampere turn corresponds to 0.125 oersted.

iment one ampere-turn corresponds to 0.125 Oe. A field H_i caused by 1 ampere turn corresponds to $\Delta\omega = 1750 \text{ c/s}$ in the region $H_0 = 0.5$ to 1 Oe. This rate can certainly be measured with an accuracy of 0.1%. Since it is reasonable to wind coils up to 10^6 turns, currents larger than $1 \mu\text{A}$ can be integrated with an accuracy of 0.1%.

The described work was done as part of a research for integrating systems to be used in nuclear scattering experiments with the external

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THE 2.5 MW H.F. AMPLIFIER OF THE CERN LINEAR ACCELERATOR

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Received 19 May 1959

The report contains a description of the grounded grid amplifier using tuned coaxial lines designed for meeting H.F. power requirements of the CERN linear accelerator. Performance curves are given for this amplifier terminated

in a matched load or short circuited. Guidance is given in choosing a suitable working point to prevent damage in the cavity and in the cables due to an external mismatch.

1. Introduction

One of the most important technical differences between the various linear accelerators already existing or under construction seems to be the method of generating and feeding in the H.F. power. With reference only to proton linear accelerators, there has been a tendency in the last ten years to concentrate the power in a progressively smaller number of oscillators or amplifiers. A large number of units in parallel increases the difficulty of synchronisation, which must be very accurate to keep the whole system in phase during the pulse. In the 32 MeV Berkeley machine, the accelerating cavity was fed by all the oscillators in parallel so tightly coupled that the only possible oscillation was at the natural frequency of the cavity. The simplest method of synchronisation however, seems to be to use final amplifiers fed in parallel by a common drive, which can be crystal controlled. This solution was adopted in the Minnesota and CERN linear accelerators. In both the accelerating structure is made in three sections electrically independent, each of them fed by an amplifier. The complications of electrical coupling between the various amplifiers are thus avoided. It is obvious that a reduction in the number of units involves an increase of the H.F. peak power that each unit must deliver. The technical effort in recent years has therefore been turned to the construction of more and more powerful oscillators and ampli-

fiers. Table 1 shows the number and output power of H.F. units of various American and European linear accelerators. The evolution from the 1948 H.F. system of the Berkeley accelerator to that of the injector for the 30 GeV Brookhaven machine is evident.

2. The CERN H.F. System

Although it is not within the scope of this paper to describe the whole H.F. system proposed for the CERN linear accelerator, a brief outline will be given of the H.F. chain, which is shown schematically in fig. 1.

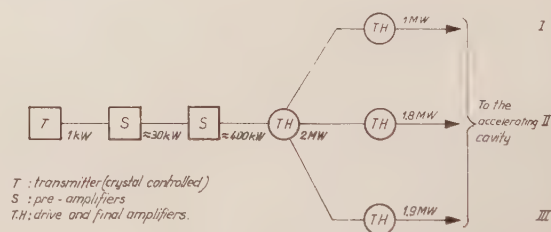


Fig. 1

The three final power amplifiers, with power outputs of 1, 1.8, 1.9 MW respectively are driven by an amplifier of the same type; this in turn is driven by a chain which includes a transmitter and two amplifier units in cascade. The level of power in the different stages is indicated in the figure.

3. The 2.5 MW Unit

3.1. GENERAL CONSIDERATIONS

The development of the project of the 2.5 MW unit was based on the following data:

† Now at the International Atomic Energy Agency, Vienna.

TABLE I
List of proton linear accelerators

	Energy	Total HF peak power	Type of final unities	Number of final unities	HF peak power per unit	Type of tube	Repetition rate	Pulse length	Frequency	Notes
	MeV	MW		No	MW		cps	μ sec	MHz	
Berkeley	32	2.2	oscillator	26	0.09	GL-434 triode (4)	15	600	200	year 1948
Berkeley	10	0.5	oscillator	9	0.25	3W 10000 A3 (EIMAC)	1/6	500	200	year 1950
University of Minnesota	68	6.4	resatron	3	0.17	3W 10000 A3 (EIMAC)	60	300	200	Bevatron injector
Brookhaven National Laboratory	50	≈ 5	klystron†	1	5	(EIMAC)	5	200	200	30 GeV machine injector
CERN	50	≈ 5	grounded grid amplifier	3	0.8; 1.8; 1.9	TH 470 (CFTH)	1	200	200	25 GeV proton synchrotron injector
Harwell AERE Lab.	50	≈ 5	grounded grid amplifier	3	0.83; 1.71; 1.86		50	400	200	

† Under consideration.

frequency	202.5 MHz (1.48 m wavelength)
H.F. peak power output	> 2 MW
pulse length	200 μ sec
repetition frequency	1 pulse/sec
H.F. input power	< 400 kW.

As one can see, the frequency and the power suggest the choice of a "common grid" amplifier with tuned coaxial-line circuits. This type has the advantage of good separation of the input and output tuned circuits. It follows that the neutralizing system is in general very simple and often unnecessary. In our particular case neutralisation at 60 MHz was considered desirable and fitted in the prototype, but the shielding action of the grid was found to be so effective that any neutralizing system was abandoned altogether in the later versions. The tuned coaxial-line circuit arrangement leads also to a compact design of the amplifier and limits the H.F. radiation outside the unit.

3.2. THE VALVE

The 2.5 MW cavity uses the triode TH 470, which has been specially designed and constructed by "Compagnie Française Thomson-Houston" to fulfil CERN requirements. Some of the more important data of this tube are quoted below:

Cathode material	Thoriated tungsten
Heater data	Directly heated $V_f = 15$ V. $I_f = 400$ A
Capacitances:	
anode to grid	55 pF
grid to cathode	105 pF
anode to cathode	1.5 pF
Limiting values:	
anode voltage	40 kV
bias voltage	—1.5 kV
peak cathode current	600 A
max. anode dissipation	5 kW
max. grid dissipation	1 kW
Cooling system:	
for anode	water evaporation
for cathode and glass	blown air.

Further information will be found in "Revue Technique CFTH" (ref. 1)).

3.3. THE COAXIAL-LINE CIRCUITS

The simplified equivalent circuit of the common grid amplifier is shown in fig. 2. The

coaxial-line anode-grid and grid-cathode circuits can be tuned independently by means of movable plungers. The grid-cathode line is contained within the anode-grid line to minimize the height of the structure (fig. 3). Both lines operate in the $\frac{3}{4}\lambda$ mode. The anode D.C. blocking capacitor C is also of the coaxial type. It has to

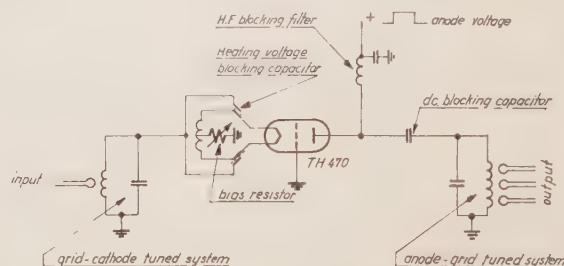


Fig. 2

withstand at least 50 kV pulse voltage and at the same time present a very low reactance at 200 MHz. An attempt to use a "lumped" type capacitor composed of aluminium disks insulated by mica led to a bulky structure that was rather transparent to H.F. radiation and left high voltages dangerously exposed. The solution adopted is the quarter wavelength coaxial line shown in fig. 4. The diameter of the inner cylinder has been chosen as small as possible to permit a reasonable overall diameter for the unit without hindering quick removal of the valve. The outer diameter has been so chosen that the distance $b-b'$ can withstand both H.F. and D.C. voltage. During the tests some trouble was experienced with breakdown in the upper part of the cavity, inside the pyrex tube and between the pyrex tube and the lid. It was found that the level of the cooling water in the anode jacket was rather critical. A change of ± 1 cm from the optimum level is equivalent to a change of at least 7 cm in the length of the pyrex tube for the same safety factor. The valve is held by three ceramic supports at 120° . The shape of these supports

¹⁾ J. P    , Etude du tube TH 470, Revue Technique C.F.T.H. 24 (D  cembre 1956) 13-20.

²⁾ I. Afanassieff, G  n  rateur    impulsions de 2 MW cr  te, Revue Technique C.F.T.H. 24 (D  cembre 1956) 21-29.

has been studied to avoid breakdown along the surface. It is desirable that the weakest part of the cavity should always be between two points in air. Then a random internal breakdown due, for example, to an external impedance mismatch does no permanent damage. The anode voltage is supplied through a half-wavelength stub that acts as a H.F. blocking system.

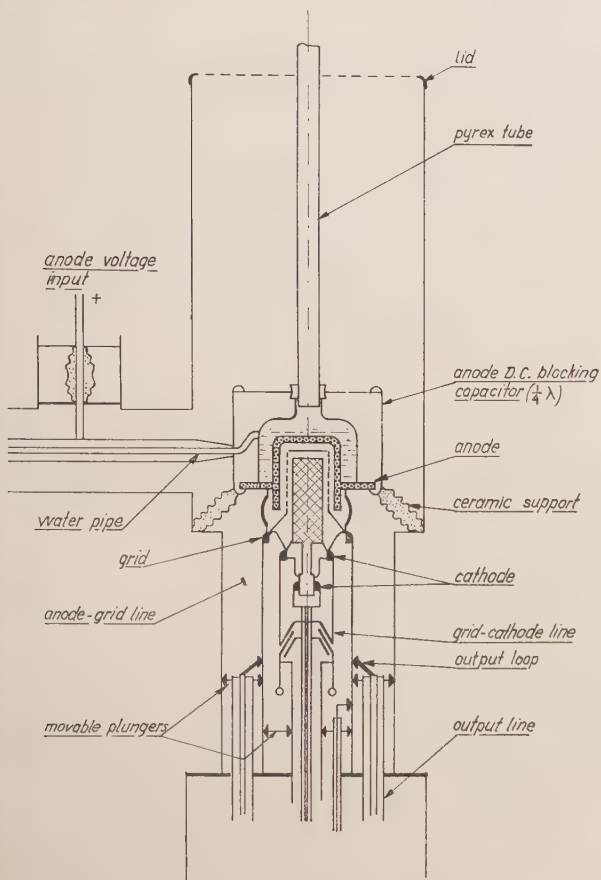


Fig. 3

3.4. THE POWER OUTPUT COUPLING SYSTEM

The arrangement for coupling the amplifier to a load consists of three untuned loops located symmetrically near the face of the anode-grid tuning plunger. This solution has been preferred to a single loop for the following reasons:

(1) The symmetry of the electric and magnetic fields is less distorted by three loops than by one.

(2) A power of 0.8 MW can be carried by commercially available coaxial cables; this would not be the case for 2.4 MW.

The complete system from the loops to a dummy load is shown in fig. 4. Rigid air-spaced coaxial lines are fixed to the tuning plunger.

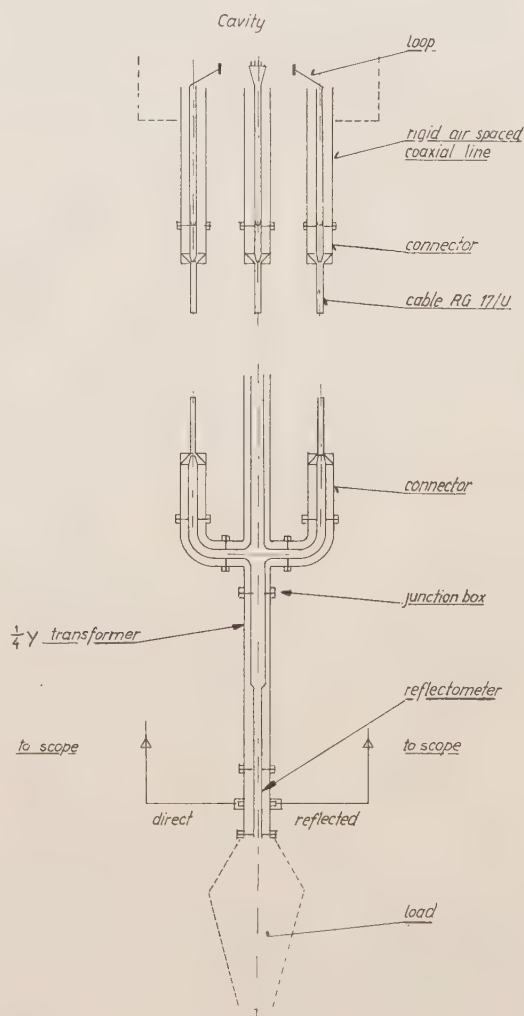


Fig. 4

Each inner conductor ends with a loop whose shape is a compromise between consideration of coupling area and voltage gradient between the loop and the cavity wall. The self-inductance of the loop has been kept low by using wide brass strip. The active area of the loop can be varied by changing the length of the inner conductor directly from the outside.

Three 50 ohm coaxial cables join the air-spaced coaxial lines to a junction box acting as a quarter-wave transformer from 16.7 ohm to 50 ohm.

The 50 ohm side of the transformer can be connected either to the input of the accelerating cavity or to a 50 ohm dummy load.

4. Cavity Performance and Measurements

The tests that have been made on the cavity can be divided into 3 principal groups:

- (a) Test without H.F. signal;
- (b) H.F. power tests with matched dummy load;
- (c) H.F. power tests with short circuit at the end of the output line.

The test assembly is shown in schematic form in fig. 5.

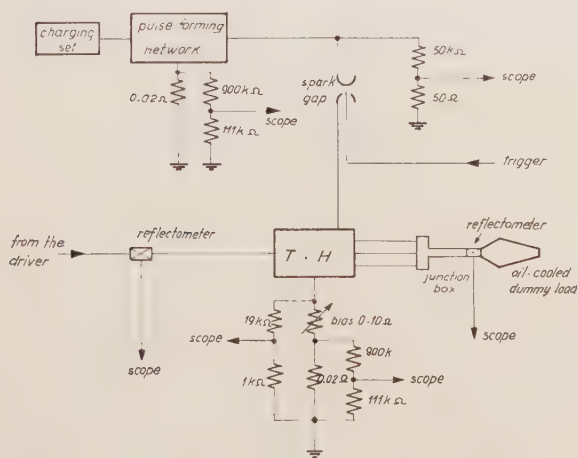


Fig. 5

The anode voltage pulse is supplied by a pulse-forming network and can be varied from a few kilovolts up to 50 kV by changing the charge voltage of the line.

The value of the pulse voltage is read through a 1000/1 voltage divider.

The input H.F. power is supplied by a driver and can reach 400 kW. Its value is read through a reflectometer (ref. ⁵) at the output of the drive unit. Another reflectometer measures the output power. The anode and cathode currents are

measured across a 0.02 Ω non inductive coaxial resistor. The bias voltage can be varied by a 10 Ω potentiometer between cathode and ground.

The dummy load provided for the tests of group (b) consists of a 50 Ω carbon film resistor within an exponential outer conductor. This dummy load is oil cooled and a system is provided for the calorimetric measurement of the power (ref. ³).

The tests of group (c) are carried out by terminating the line with a movable short-circuit plunger mounted in half-wavelength line.

4.1. TEST WITHOUT H.F. SIGNAL

The valve and the coaxial-lines stand easily 40 kV anode voltage. Some breakdown was experienced at 65 kV in the stub holding the anode voltage cable. Higher anode voltage may cause breakdown inside the tube.

4.2. H.F. POWER TESTS WITH MATCHED DUMMY LOAD

4.2.1. A set of tests was carried out to find the optimum size of the output loops. The cavity was tuned and the anode voltage fixed at 40 kV. The area of the loops was decreased by steps and the drive power varied between 150 and 330 kW. The relation between loop size, drive power and output power is given in fig. 6. The loop area is expressed in percentage of the optimum value (in our particular case 12.43 cm²). Every position of n corresponds to a variation of 8.5 n%. The dotted line limits a region of probable breakdown inside the cavity due to undercoupling. A study of fig. 6 shows that a good compromise between safety and efficiency can be reached by choice of the point A (it corresponds in our case to ≈ 13 cm²).

4.2.2. With the loops fixed in this position, the anode voltage at 40 kV and the cavity accurately tuned we have reached a power level of 2.5 MW $\pm 5\%$. Some breakdown occurred in the pyrex tube (see fig. 3) and between the walls of the anode-grid tuning coaxial line. We could get rid of the breakdown in the pyrex tube by lengthening it, but this hardly seemed worth while since at slightly higher power,

³) E. Zaccheroni, High frequency power meter for operation at 2 MW pulsed power, CERN/PS Report (in preparation).

⁴) P. Bramham, A moulded connector for RG17/U coaxial cable, CERN/PS Technical Note (in preparation).

⁵) E. Zaccheroni, Power flow monitors for the Linac H.F. system, CERN/PS Report (in preparation).

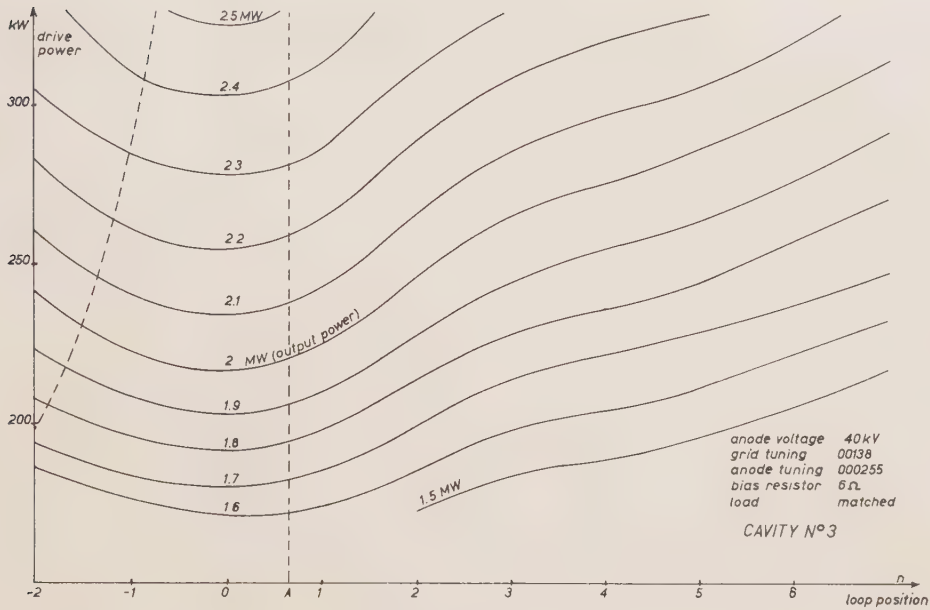


Fig. 6

breakdowns across the cavity become rather frequent. Several breakdowns have been ex-

perienced also when slightly mismatching the dummy load impedance. Measurements have been carried out of the output power as a function of anode voltage and drive power. The relationship is given in fig. 7.

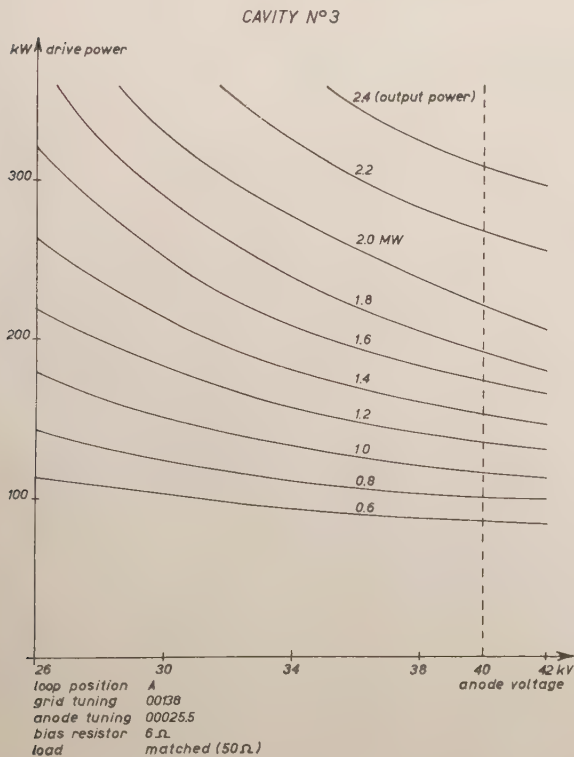


Fig. 7

4.3. H.F. POWER TESTS WITH SHORT CIRCUIT AT THE END OF THE OUTPUT LINE

4.3.1. The short circuit problem

The tests carried out on the amplifier when connected to a matched load do not give a sufficient idea of its performance if connected to the accelerating cavity. In the condition of working as a final amplifier there are two possibilities of short circuit. The first, that we can define as normal because it appears at the beginning of each pulse, is due to the difference between the build-up time of the field in the accelerating cavity and the rise time of the power of the amplifier.

The second is random and may be caused by a flash-over inside the accelerator or by a refusal of the field to build up. Both short circuits produce a standing wave in the output line and consequently points of increased voltage. There is, however, a difference between the two

types of short circuit: in the first case the antinode is fixed, in the second one it can change according to the position where power reflection occurs. The voltage at the antinodes may damage the lines if they are not designed to withstand safely twice the normal voltage, but, as will be seen later, a solution of this kind is rather complicated. A better solution is to arrange the various parameters so that the

sliding short circuit plunger and for different values of drive power.

The results are plotted in fig. 8. The curves show how in a particular position ($x = 60$) it is practically impossible to prevent a breakdown inside the amplifier cavity even with very low drive power. At a distance of a quarter wavelength ($x = 23$) however it is possible to increase the drive power without causing

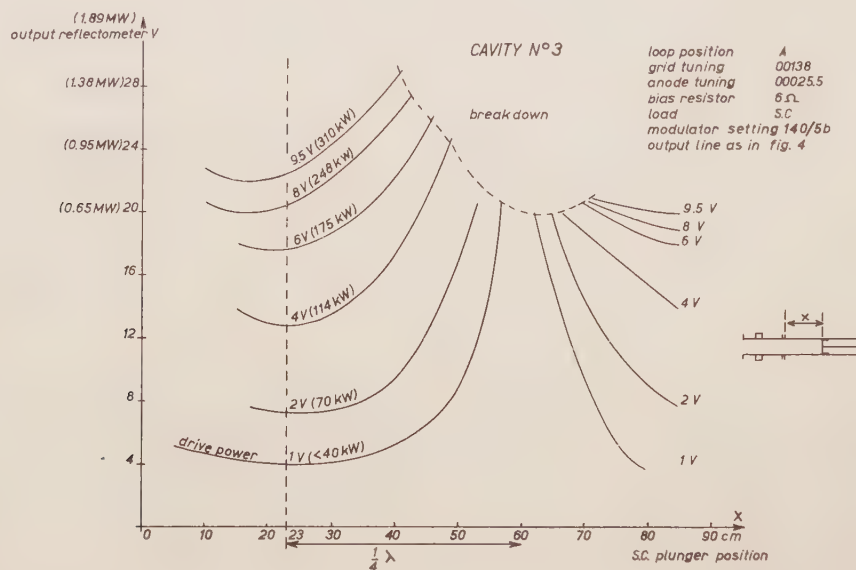


Fig. 8

amplifier reacts to the short circuit condition by an automatic reduction in output power. The result will then be that the line is subjected to twice the voltage for only a very short time, the voltage falling for the rest of the pulse.

4.3.2. Forward (or reflected) power as a function of the short circuit position

The influence of the short circuit position on the forward output power will now be studied. The cavity is put in the test condition of fig. 7 but the matched load has been replaced by a sliding short circuit. In order to be as near as possible to the final operating conditions the charging voltage of the modulator was kept constant rather than the anode voltage itself. The forward output power was read by means of a reflectometer for different positions of the

breakdown. There is the alternative of changing the position of the anode-grid tuning piston keeping fixed the short circuit plunger. To investigate this, a measuring loop has been mounted on the anode-grid piston. The modulator charging voltage and the drive power were again fixed. These parameters will probably be different in the final installation; so the curves of fig. 9 will only have qualitative significance. They show that it is possible to find a resonance of the anode cavity and output lines system for different combinations of the positions of the piston and of the plunger. The dotted curve shows how the variation of the voltage of the forward (= reflected) power in the output line follows the resonance. It also shows, as was expected, that a displacement of a few millimeters of the anode-grid tuning piston would

correspond to a displacement of several centimeters in the short circuit plunger. It follows that in the case of a fixed short circuit it will be useful to choose the length of the output line and the position of the anode-grid tuning piston so as to be as far as possible from resonance.

1.89 MW into a matched load ($v = 13.7$ kV) corresponds in the three curves a, b, c to 0.88, 0.8, 0.7 MW (18.7 kV, 17.9 kV, 16.7 kV at the antinodes). It will be seen that these maximum values will considerably simplify the desing of the output lines. The case of an erratic short

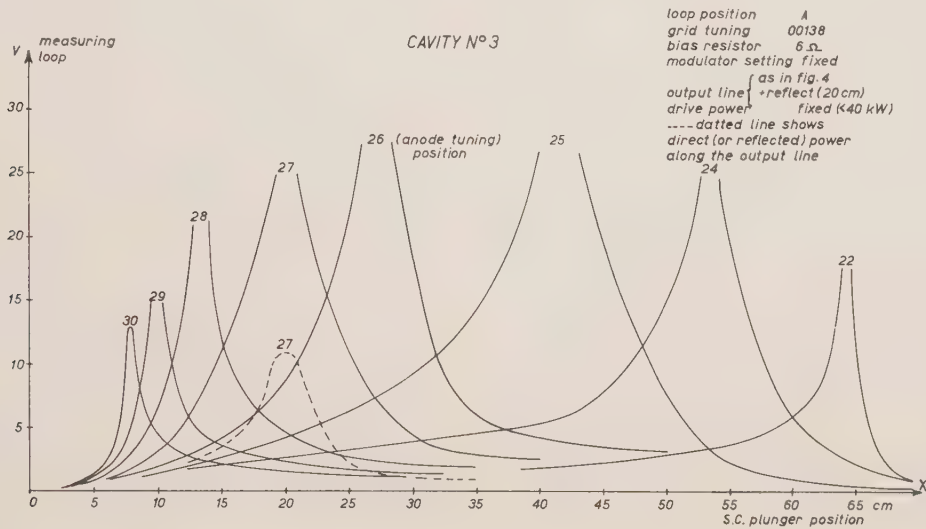


Fig. 9

4.3.3. The reaction of the amplifier to a sudden short circuit

The power output available into a matched load must, however, still be taken into account in making any changes to the position of the anode piston. When the output power requirement is very high, anode piston setting is very critical and no range of adjustment is available for influencing other parameters. It follows then that the length of the output line is the only available variable.

In fig. 10 are plotted curves of various drive power levels and various modulator charging voltages when the cavity feeds either a matched dummy load or a short circuit in position $x = 23$. The curves a, b, c correspond to increasing values of the charging voltage. On the x axis is shown the output power into a matched load and on the y axis the forward (= reflected) power when the output is short-circuited. It appears that it is advantageous to work with high anode voltage (curve c). A power level of

circuit still remains to be considered. It may happen that this coincides with the position $x = 60$. The voltage at the antinodes increases (with 1.89 MW it will be 27.4 kV). But the antinodes in this case occur in a position in which the anode cavity is completely off tune: it therefore seems useful to put a spark gap at the antinode point. The position of this safety spark gap must be fixed according to the position of the anode-grid piston. It seems possible to put a protective circuit also on the input side of the cavity. In fact it was seen during the tests that near resonance of anode cavity a large reflection occurred at the input. This suggests putting a spark gap at an antinode of the input line or arranging an electronic device to react when the reflected wave increases.

5. The "Plumbing" Problem

The connection between the output loops of the amplifier and the load is made by air-spaced coaxial lines and solid dielectric cables. A

system of only rigid lines would not have enough mechanical flexibility to follow the movement of the anode-grid tuning piston, so cables are provided to connect the rigid lines at the output of the amplifier to the rigid line at the input of the load. The three output lines ($\varnothing$ 58/25), if considered without any support holding the inner conductor, have a power handling capacity of four times the maximum power required when calculated on the basis of

lines have been suppressed by simple mechanical arrangements. Particular care has been taken in avoiding sharp metal corners and in designing the spring connectors and the joints.

6. The Cables Problem

The only weak point that still remains is the connection between the air-spaced coaxial lines. The cable used is RG17/U (15.4 kV peak); it will not safely withstand a short circuit at 2.4 MW power level, but arrangement can be made as described above to reduce the antinode voltage under these conditions. This cable is however the biggest readily available and cannot easily be replaced. The connection between the rigid line and the cable is made by means of moulded connectors of special design (ref. 4)) that are being developed. A provisional connector for laboratory use has been filled with "Telcompound" filler. Its electrical performance is good if air voids are carefully eliminated but it has tendency to crack and retain dust.

7. Conclusion

As seen above the amplifier can reach the 2.5 MW level only if some precautions are taken. In particular the cooling water level, the cleanliness of the cable connectors and the impedance match have to be carefully controlled. For safety in the case of a short circuit the amplifier parameters and the line length have to be chosen as indicated in the report, after, final installation of the cavity.

Acknowledgment

The equipment described in this report was developed in the LINAC Group of the CERN Proton-Synchrotron Division and in collaboration with French Thomson Houston in Paris. Dr. Geiger of CERN and Mr. Afanassieff of F.T.H. originated the developments. I would also like to thank Dr. Hereward, Leader of the LINAC Group, for his suggestions during the course of the work and other members of CERN and F.T.H. who have taken part in the measurements.

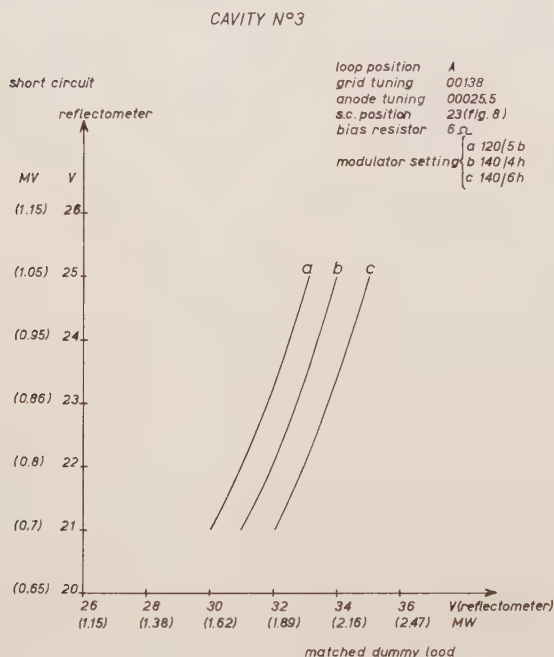
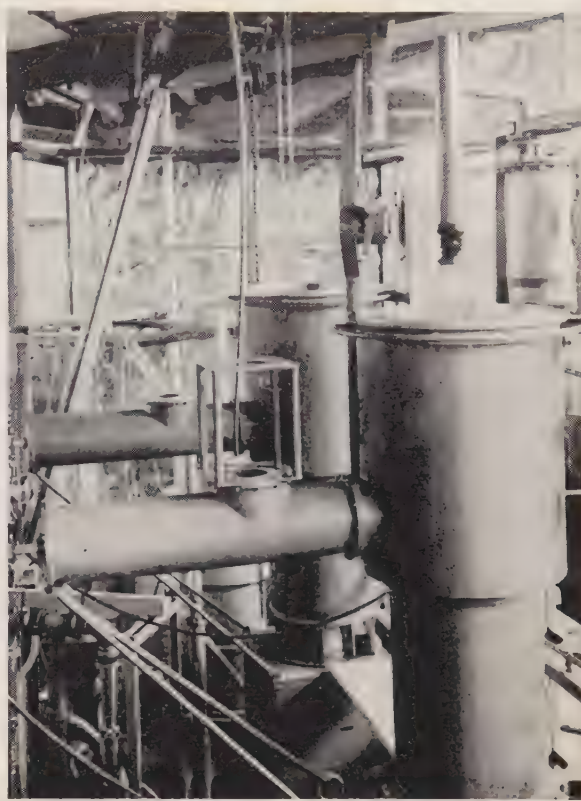


Fig. 10

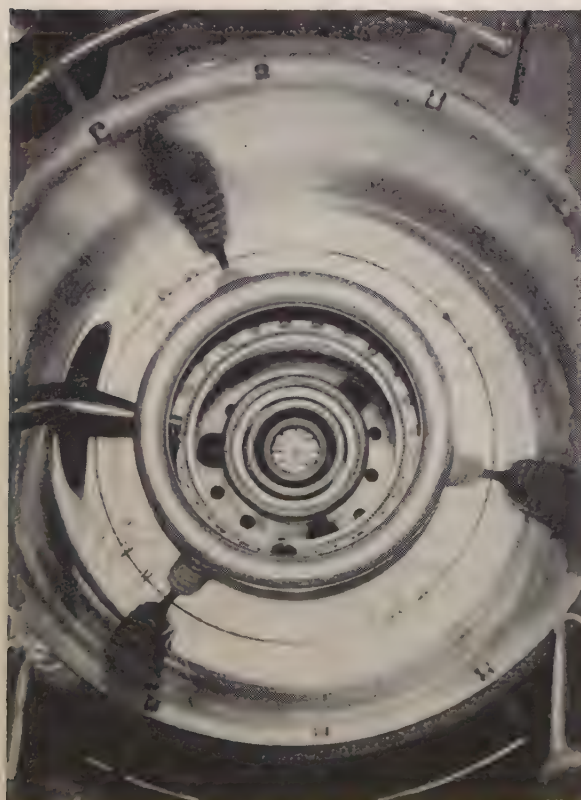
breakdown at 30 kV/cm. The presence of dielectric cross supports decreases the breakdown voltage so much that the safety factor at full power is completely lost. Plexiglas rods flash over with tracking at low power (0.6 MW). Polystyrene is better (0.8 MW) but not sufficient. An attempt has been made to hold the inner conductor directly by the loop itself. This involves using strong loops fixed at the tuning piston. The top of the loop can slide along the inner conductor to change the effective area. Concentricity is assured by the cable connector screwed on the opposite end of the line. The other teflon or polystyrene supports along the



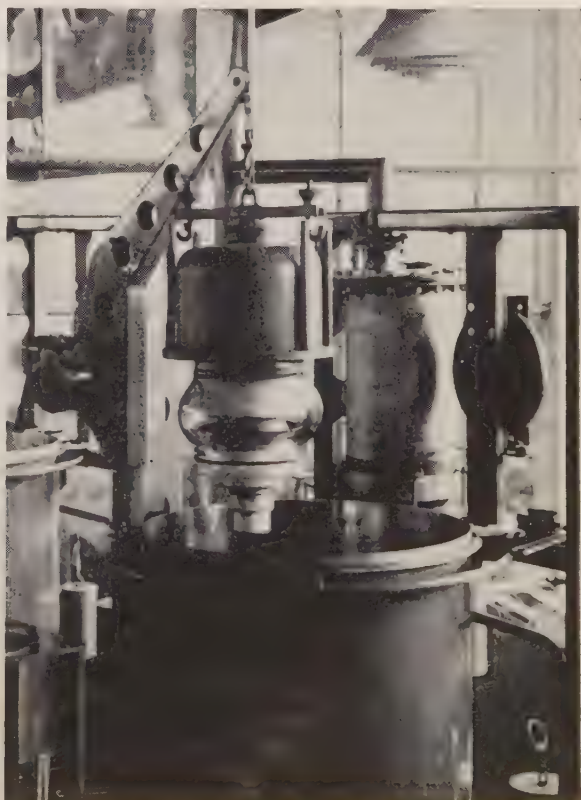
General view of the cavity.



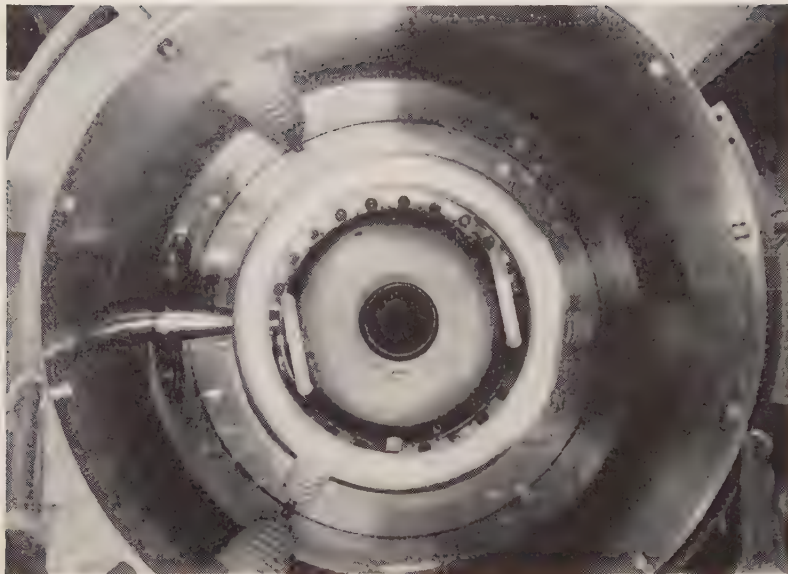
View of the cavity partially opened showing the cooling system and the anode voltage stub.



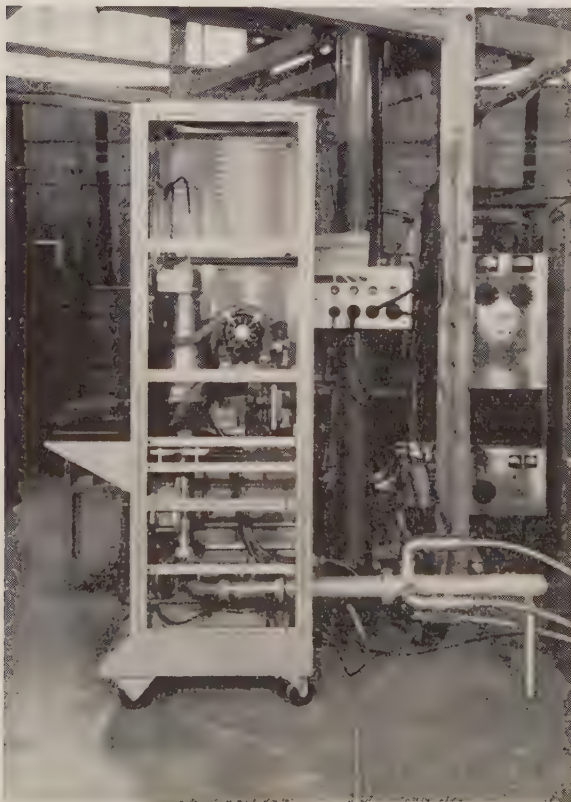
Top view of the cavity without the TH 470 triode.



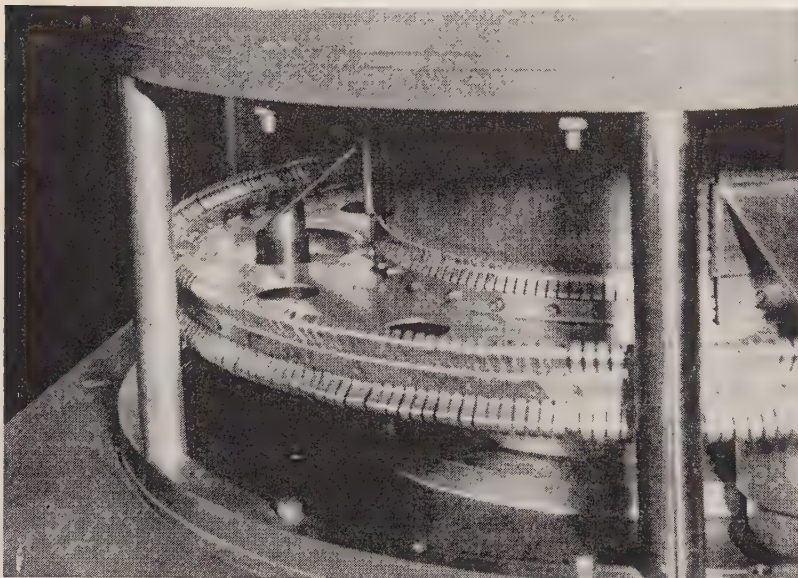
The triode TH 470 being lowered into the cavity.



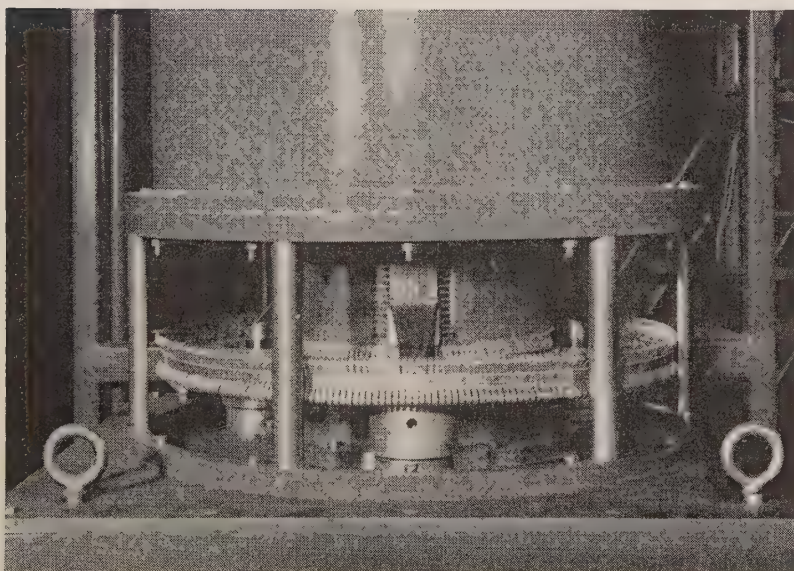
Top view of the cavity with the TH 470 triode in position.



The junction box, the reflectometer and the dummy load.



Anode-grid tuning piston and the output loops.



ON SOME PROPERTIES OF THE RADIO FREQUENCY ION SOURCE WITH LONGITUDINAL MAGNETIC FIELD

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Comisión Nacional de la Energía Atómica, Buenos Aires, Argentina

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A description is given of a radio frequency ion source of the Thoneman type, but with a coaxial magnetic field. It is shown that with proper choice of the measured variables

simple straight line plots are obtained which can be given easy interpretation and be useful in further developments. Some limitations of this type of source are also shown.

The radio frequency (R.F.) ion source developed by Thoneman¹⁾ is often used as a source of protons or of deuterium ions, specially for low energy accelerators, because of its high yield in atomic ions. In many of the papers on the subject the influence of the magnetic field is discussed. Following von Ardenne²⁾ we may classify R.F. ion sources into three types:

- (1) with no magnetic fields³⁻⁶⁾;
- (2) with a magnetic field normal to the axis of the system, (transversal field)⁷⁻¹⁰⁾;
- (3) with a magnetic field in the same direction as the axis of the system, (longitudinal field)¹¹⁻¹⁴⁾.

In his original work Thoneman did not make use of a magnetic field. However, in later works¹⁵⁾ he observed that the proton yield, as well as the total ion current were increased by the presence of a magnetic field (transversal as well as longitudinal) but he also found that similar results could as well be obtained by just increasing R.F. power.

Beauregard¹²⁾ and Allison and Norbeck¹³⁾ claim much larger beam currents with a longitudinal field. However, high currents have also been reported with no field at all by Eubank, Peck and Truell⁵⁾. In the transversal field case, the increase is not so large, although it is important. There also has been reported a resonance effect between magnetic induction and oscillator frequency^{8, 9)}, associated with the cyclotron resonance condition for electrons.

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Our interest in a R.F. ion source arose when building a 200 kV accelerator, which was supposed to be used as a neutron source, making use of the well known reaction:



As we needed a rather strong ion source, in order to compensate with current for the small cross section of the reaction at the low voltages used, we investigated how far could the different ion source parameters be pushed. The work started when the only publication available at that time giving enough building details was the one by Moak, Reese and Good¹⁴⁾, our design matches more or less theirs. In an early stage

¹⁾ P. C. Thoneman, J. Moffat, D. Roaf and J. H. Sanders, Proc. Phil. Soc. (London) **61** (1948) 483.

²⁾ M. v. Ardenne, Tabellen der Elektronenphysik, Ionenoptik u. Übermikroskopie, Bnd. **1** (1956).

³⁾ L. K. Goodwin, Rev. Scient. Instr. **24** (1953) 635.

⁴⁾ M. de Lareymondie, J. Salmon and J. Watsbrun, J. de Phys. et Rad. **13** (1954) 117.

⁵⁾ H. P. Eubank, R. A. Peck and J. Truell, Rev. Scient. Instr. **25** (1954) 989.

⁶⁾ O. Reifenschneider, Ann. der Physik **14** (1954) 33.

⁷⁾ M. B. Nicolice and M. U. Crnilovic, Bull. Inst. Nucl. Scs. B. Kidrich **34** (1953) 29.

⁸⁾ H. Neuert, H. Stuckenberg and H. P. Weidner, Zeit. f. Angew. Phys. **6** (1954) 303.

⁹⁾ H. Neuert, Zeit. f. Naturforschung **4a** (1949) 449.

¹⁰⁾ C. P. Swann and F. J. Swingle, Rev. Scient. Instr. **23** (1952) 636.

¹¹⁾ R. N. Hall, Rev. Scient. Instr. **19** (1945) 905.

¹²⁾ J. de Beauregard, J. de Phys. et Rad. **14** (1953) 547.

¹³⁾ S. K. Allison and F. Norbeck, Rev. Scient. Instr. **27** (1956) 285.

¹⁴⁾ C. D. Moak, H. Reese and W. M. Good, Nucleonics **9** (1951) 18.

¹⁵⁾ Reports of the Amsterdam Conference on Ion Sources, (Amsterdam, 1949).

of the work the importance of the magnetic field was realized and therefore it was specially investigated how the characteristics and properties of the ion source depended on applied magnetic field.

Technical Description

After several trials on a bench stand the ion source was placed on the top of the accelerator

into a small spot. The discharge tube is cooled by air from a blower.

For the radio frequency oscillator a pair of TB 3/750 tubes was used, working in push-pull. This could give more than 1 kW of power at 110 Mc/s, but this was usually limited to about 300 W with a variac control on the anode supply. At about 500 W the glass of the discharge tube softened. The big tubes were chosen for

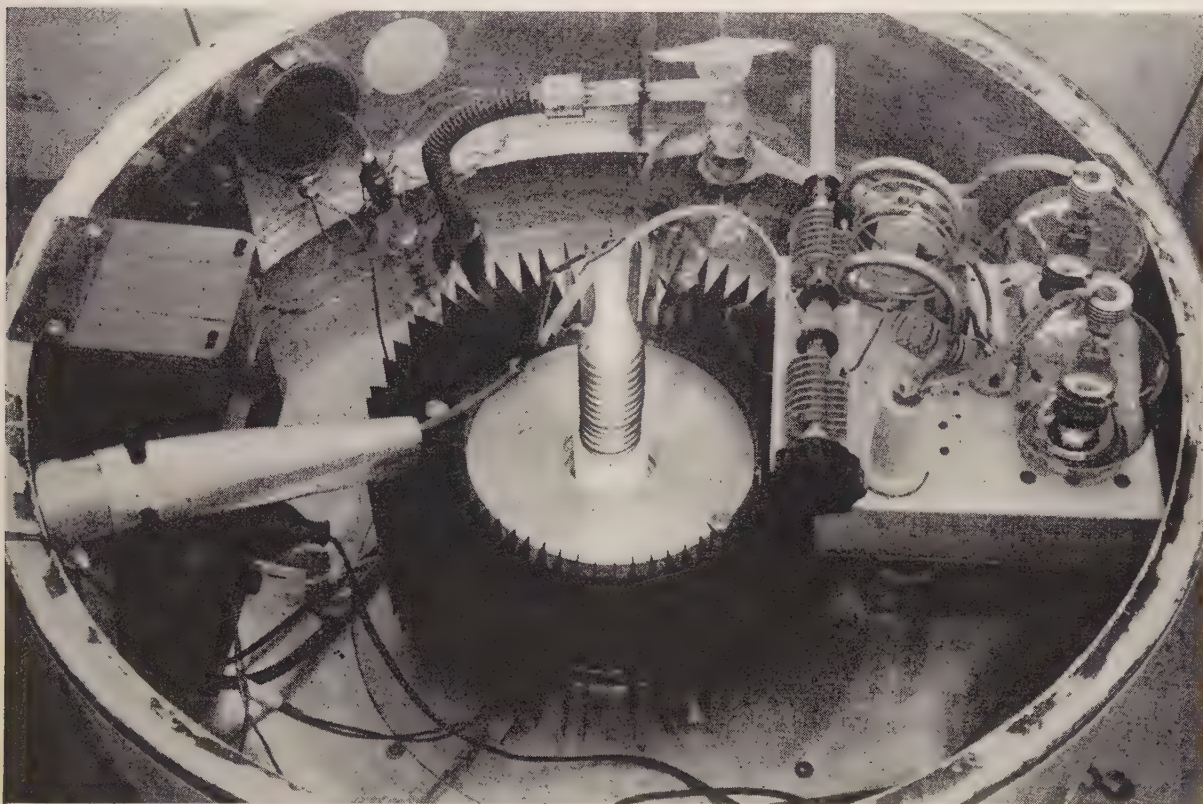


Fig. 1. General view of the assembled ion source, with its external iron yoke, air cooled coil.

tube. It may be seen on fig. 1. The different parts of the system are as follows:

The discharge tube is made of pyrex glass with a bottom shaped according to Moak, Reese and Good design¹⁴). The upper part is conical in shape, slightly bent off axis. This allows the intense cathode ray beam issuing from the probe (or extraction canal electrode) to spread its energy over the glass surface. Otherwise the glass melts almost instantly, because the strong longitudinal field focuses the beam

reliability. The oscillator was adjusted so it would operate even with very low anode voltage.

The R.F. coupling is rather unusual: A coil of about 15 turns of 5 mm copper tubing is connected at one end only to one of the feeders of a 300 ohm line (standard TV antenna line). The load matching is achieved by inductive coupling to the oscillator tank coil and a pair of series tandem capacitors. The coil works like an end fed antenna. This coupling method was used after several trials, because it was necessary to

avoid DC on the R.F. electrodes, which could be in contact with the hot glass. This produced glass electrolysis and breakdown.

The magnetic field was produced with four coils of about 3000 turns each of 0.25 mm enameled copper wire. To increase the coil efficiency an external iron yoke is used. Care was taken to insure good heat transfer from the coils to the iron yoke, which was fitted with

open suddenly, causing arcing in the accelerator tube.

The performance of the ion source can be better tested without high voltage on the accelerator tube and with some device which allows the measurement of the ion beam when it leaves the extraction canal, and before acceleration. For this purpose the accelerator's top is grounded, the usual target withdrawn and a

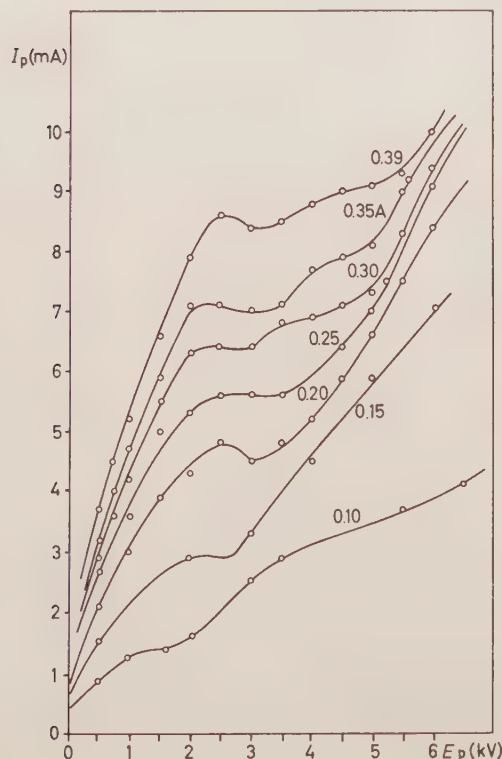


Fig. 2. Probe current versus probe voltage, plotted taking magnetic field coil current as parameter.

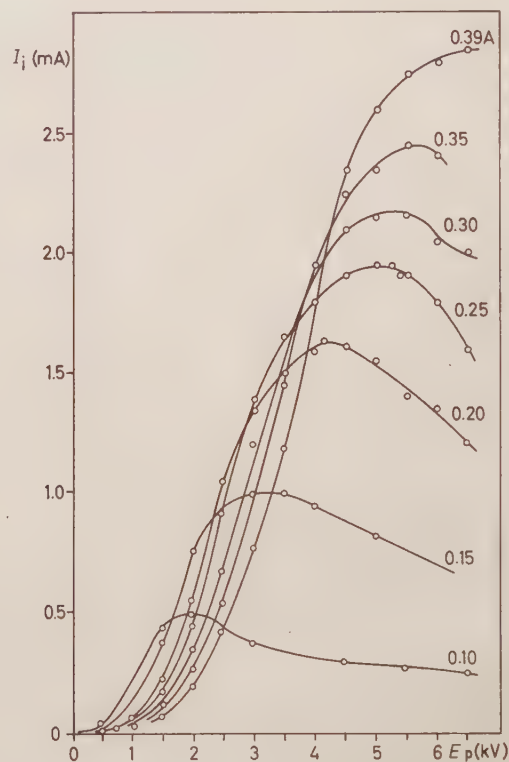


Fig. 3. Ion beam current versus probe voltage, again with field current as parameter.

cooling fins. The coils are wound on brass spools, vacuum impregnated and tightly clamped by the iron yoke. Usually only three sections are used giving about 800 gauss in the center, with 440 volt and 0.39 A. With all four sections the field is about 1000 gauss.

The hydrogen (eventually deuterium) gas flow is controlled with a palladium leak. Commercial needle valves were found unsuitable and even dangerous. They tend to stick and then

long brass bar, running all along the accelerators tube axis, is introduced. This bar has on its end a 3 cm diameter disc which takes place inside the first focusing electrode and so receives directly the ion beam issuing from the canal. During all the measurements this electrode is earthed through a milliammeter. The first focusing electrode is kept about 10 kV negative to hinder secondary electron emission from the ion collecting electrode.

Ion Source Characteristics and Results

The properties of ion sources may be given by presenting some sets or families of characteristics curves in which, i.e., ion beam or probe current are plotted against extraction (probe) voltage, the R.F. power and/or gas pressure being parameters^{3,4,9}). Following this trend we have plotted on fig. 2 the probe current I_p versus probe voltage E_p , magnetic field current

These maximums have been observed by Lareymondie⁴) and by Goodwin³) for sources with no field and by Nikolic and Crnilovic⁷) for a source with transversal field. The maximums of fig. 3 match fairly well the minimums of fig. 2.

Much easier interpretation of the results could be obtained if we take from fig. 3 the maximum values of the ion beam current $\bar{I}_1$, for each set of

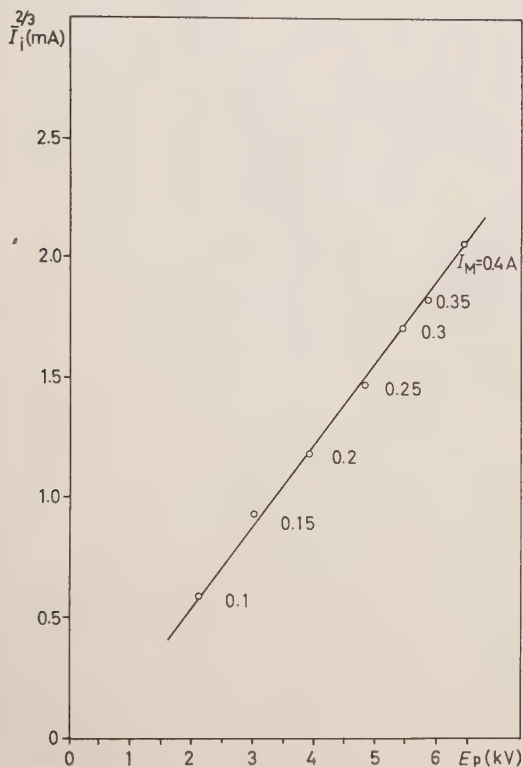


Fig. 4. The $\frac{2}{3}$ power of the maximum beam current versus probe voltage as parameter. The linear relationship proves the space charge limited character of the beam extracting process.

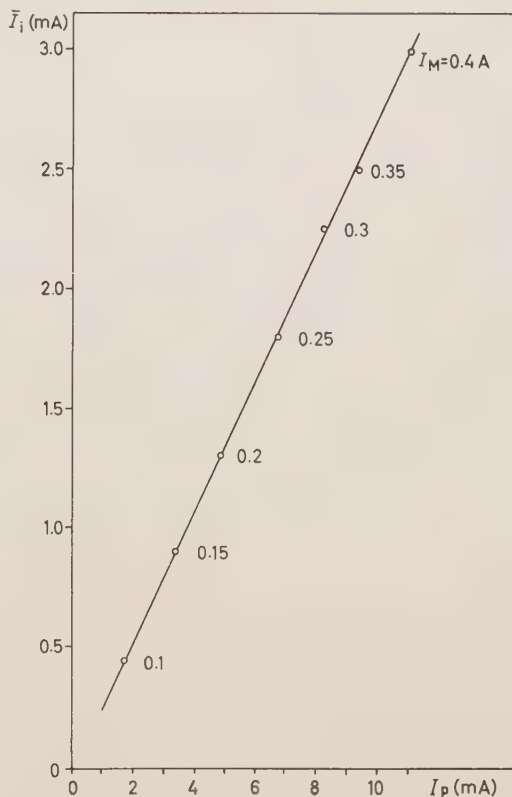


Fig. 5. Maximum beam current versus corresponding probe current. The linear relationship proves the independence of plasma boundary shape upon plasma density.

I_M being the parameter. (The R.F. power was kept constant at about 300 W.) The dips observed are similar to the ones observed by Nikolic and Crnilovic⁷) for a source with a transversal field and by Eubank, Peck and Truell⁶) with no field. They are interpreted as corresponding to the conditions when the ions are focused into and through the canal.

On fig. 3 the ion beam current I_1 is plotted versus probe voltage E_p , with I_M as parameter. There is a definite maximum on each curve.

parameters (field current I_M and probe voltage E_p) and take this as new dependent variable. These are the values which characterize the source.

Taking the $\frac{2}{3}$ power of $\bar{I}_1$ and plotting this versus probe voltage E_p (fig. 4) we get a straight line which proves the space charge limited character of the process.

Plotting $\bar{I}_1$ versus probe current I_p (fig. 5) we get also a straight line. This means that a constant fraction of the available ions is focused into and

through the canal. (The slope of this line is 0.27, but this does *not* mean that the 27% of the ions are focussed into the canal. One must also take into account secondary electron emission.) In view of Thoneman's description of the source mechanism this result could be interpreted as the shapes of the plasma boundaries and of the ion beam are independent of plasma density in ions, at least when the beam is properly focused into the canal.

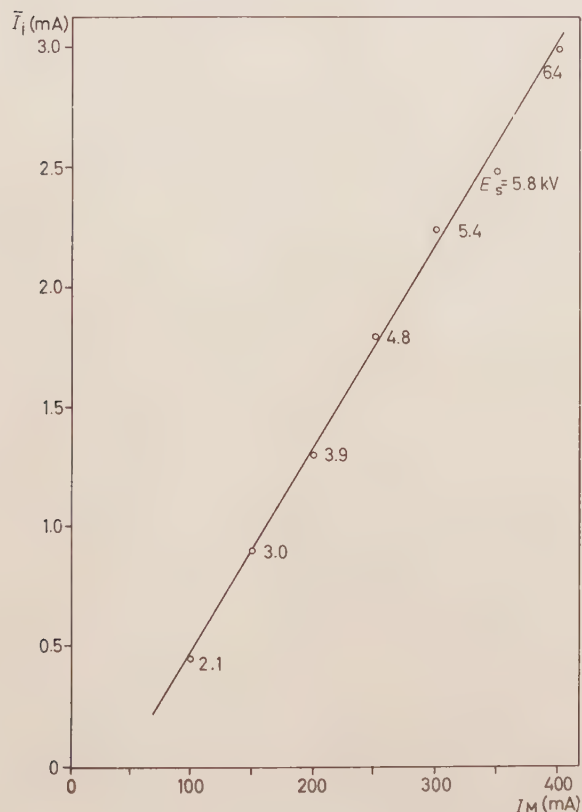


Fig. 6. Maximum beam current versus magnetic field current. The only action of the field is probably increased ionization efficiency, and not focusing action.

Fig. 6 shows the plot of I_i versus field current I_M , which is also a straight line. On this basis the effect of the magnetic field can be interpreted as simply increasing the ionisation efficiency by electron path lengthening (not a focusing action). This means increasing plasma

density in ions. The yield of the ion source depends on how many of these ions can be passed through the canal, and this is limited by the probe voltage (7 kV in our case) and breakdown problems.

The ion beam current and the general performance of the ion source can be much improved if the extraction canal is given a shape approaching the theoretically expected beam shape (Spangenberg¹⁶). Fig. 7 shows the shape and dimensions of the canal used. The focusing

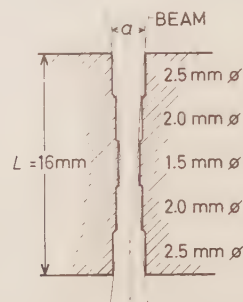


Fig. 7. Shape and dimensions of the extracting canal.

voltage needed could be reduced increasing the canal diameter, but this will bring another problem: that of the gas throughput. The gas throughput is proportional to d^3/L and the beam current to $(d/L)^2$. This limits the diameter to some millimeters.

The gas pressure in the discharge tube is a critical parameter⁴). It has a sharp optimum value at about 10^{-2} mm, which we unfortunately have not been able to measure exactly. It is independent of R.F. power or magnetic field. It is usually considered independent upon oscillator frequency. To prove this the source was operated with a 10 Mc/s oscillator (much lower than the usually reported oscillator frequency). The optimum pressure observed was much higher than with the 110 Mc/s. oscillator, as was proved by the increase in the accelerator tube pressure, which rose from 2×10^{-5} to more than 10^{-4} mm.

¹⁶ K. R. Spangenberg, Vacuum tubes (McGraw-Hill, 1949).

NOTES ON THE DESIGN OF GLOW DISCHARGE VOLTAGE STABILIZERS FOR PHOTOMULTIPLIER TUBE POWER SUPPLIES

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A series of high stability neon glow discharge tubes (OG3/85A2) was used to stabilize 1685 volts for the dynode resistance divider of a photomultiplier tube to an accuracy

of $\pm 0.2\%$. The limit of stability and the ageing phenomena for the tube operating at reduced currents are discussed but not understood.

1. Introduction

It is generally recognized that the gain stability of a photomultiplier tube may be sharply dependent upon the constancy of the voltage distributed to the various dynodes. Long term voltage stability, excellent reset characteristics, and an expected lifetime of many years are known features of several glow discharge tubes developed during the last 15 years which make them extremely attractive as high voltage-low current stabilizers. The purpose of this report is to review the published work on the new glow discharge tubes, to discuss their application to photomultiplier voltage stabilizers, and finally to describe our experience in the use of this type of voltage source.

2. Stability Measurements

The basic principles of voltage stabilizers in general have been excellently described in a book¹⁾ by F. A. Benson, University of Sheffield, England. Benson lists several hundred references which deal with voltage stabilization problems, circuitry in particular, and special applications. Chapter 3 discusses voltage stabilization by means of the glow discharge tube and is of interest in this discussion. Many tube types, including some made in the United States, England, and Holland, are compared. Data are

given for initial drift, some long term drifts, voltage jumps, temperature coefficients, striking and operating voltages, and voltage-current characteristics. On the basis of the Benson data, the most interesting tube for further study is the special high stability neon tube type 85A1†, which was the direct result of the pioneering work of T. Jurriaanse²⁾ *et al.* at the Philips Research Laboratory, Eindhoven, Netherlands, in 1946. Later (1952–53) a smaller, seven pin version of the 85A1, named the 85A2, was manufactured. It is claimed³⁾ that after an initial 100 hour running time, the maximum variation of operating voltage over any 8 hour period will be better than 1 part in 10^4 , providing an initial period of 3 minutes is allowed for warming up. The temperature coefficient is given as -4.0×10^{-3} volt/°C per tube, which is only slightly larger (percentage-wise) than the coefficient for a Weston standard cell. By comparison, it will be recalled that a properly aged and temperature controlled standard cell has a voltage stability of about 1 part in 10^5 over a period of years⁴⁾.

¹⁾ F. A. Benson, *Voltage Stabilizers* (Electronic Engineering Publishing House, London, 1950).

²⁾ T. Jurriaanse, *A Voltage Stabilizing Tube for Very Constant Voltage*, Philips Tech. Rev. 8 (1946) 272.

³⁾ Mullard Technical Handbook, Vol. 1A, Sheet Issue 3, 754-1, on Voltage Reference Tube 85A2 (Mullard Limited, London).

⁴⁾ G. P. Harnwell, *Principles of Electricity and Magnetism*, 2nd ed. (McGraw-Hill, New York, 1949) p. 140.

† The OE3/85A1 and the OG3/85A2 are distributed by the Amperex Electronic Corporation, Hicksville, Long Island, New York.

Long term (2 to 3 years) stability measurements on small samples of the 85A2 and the 5651 neon tubes have been performed by W. G. Hoyle⁵). W. H. Weber⁶) observed a number of types of glow tubes, including the 85A2 and the 5651, for several weeks. In order to stabilize the 1000 to 2000 volts for a photomultiplier tube, a number n of glow discharge tubes must be joined in series, and the average

the rate of voltage rise at the end of 3 years) than the 5651 at 3.5 mA. Weber's measurements of the 85A2 also indicate an initial upward drift for the first two weeks of about the same magnitude, and the data seem to support the manufacturer's stability figures as indicated above. The behavior of the 5651 appears to be more variable in manufacture or operation than that of the 85A2. Weber finds from a sample of

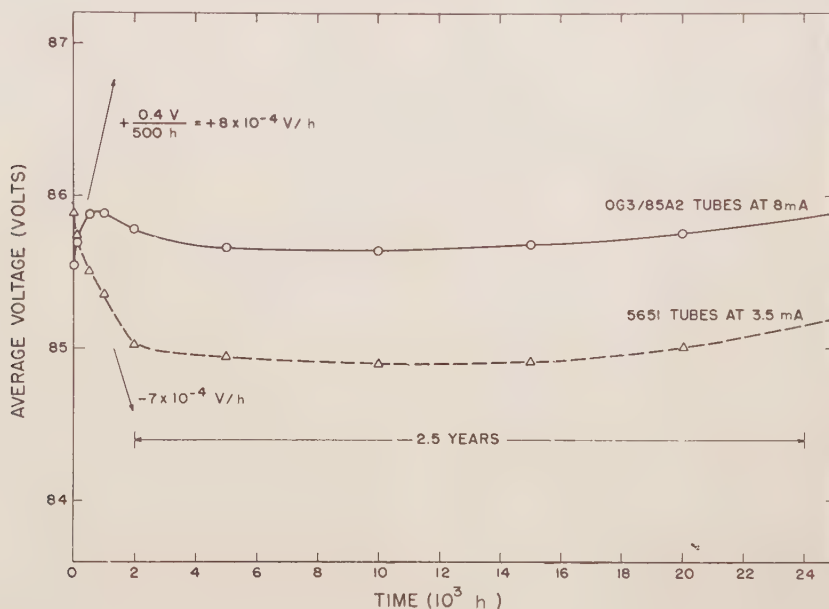


Fig. 1. Averaged and replotted data from W. G. Hoyle's long term tests of four 5651 and five OG3/85A2 gas discharge tubes (ref. ⁵)).

behavior of these tubes determined. One expects the systematic behavior of the voltage due to temperature and current changes to be the same as for an individual tube, but the relative variation of the voltage due to random fluctuations in the individual tubes will be reduced by $1/\sqrt{n}$. Therefore, we have taken the liberty of averaging Hoyle's data and have replotted these on a linear time scale in order to emphasize the smoothing of the data as well as to show the long term behavior (see fig. 1). After an initial running time of 2000 to 3000 hours, one is impressed by the remarkable stability exhibited by both tubes (85A2 and 5651) for the next $2\frac{1}{2}$ years. In detail, the 85A2 has somewhat less initial drift and appears to have a longer lifetime at a current of 8 mA (as indicated by

eight 5651's and four 5651WA's that the voltage increase with time is similar to the 85A2, whereas Hoyle's data indicate that the voltage decreases.

3. Lifetime Expectancy

The lifetime expectancy of the ordinary filament type radio tube can be and has been debated, but it seems to the author that a figure of 10^4 hours is a reasonable age at which one may expect 50% of the tubes to be useful. The gas discharge tube, however, is probably in a class by itself when longevity is discussed.

⁵) W. G. Hoyle, Long-Term Tests on the Voltage Stability of the Gas-Discharge-Tube Types 5651 and OG3, Rev. Sci. Instr. **27** (1956) 415.

⁶) W. H. Weber, Los Alamos internal report, December 1956.

Under proper conditions the glow tube will probably survive longer than the person who attempts to measure it.

The theoretical work by C. H. Townes⁷⁾ on the sputtering rates in low voltage discharge and the experimental confirmations performed by G. H. Rockwood⁸⁾ for the Western Electric neon tube 313C indicate that the lifetime of this type would be greatly extended by operating at a reduced current. Their data cover the range from 10^4 hours of life at 10 mA current to 4 hours of life at 150 mA. If the tube were to be operated at 2 mA, the extrapolated lifetime is 4×10^3 years. One assumes that a longer lifetime means that the previous observed rates of voltage change with time, due to tube ageing, would be decreased by the increased lifetime ratio. If this is so, a tube might be brought quickly to the relatively stable point as found by Hoyle and then operated at a reduced current for an indefinitely long period of time.

An interesting experiment using the 85A2 tubes would be to compare the voltage drifts with time, say the drift of 20 tubes in series operated at 8 mA with the drift from another series of 20 operated at 2 mA. The voltage drift rate should be reduced by a factor of 100 to 1000 in the 2 mA case, which is about 10^{-5} to 10^{-6} volt/h per tube. It is obvious that these small rates of change can be measured only with the aid of good potentiometer and standard cell techniques, and that the current and temperature of the tubes must be well controlled.

4. Voltage Regulation Considerations

In the usual photomultiplier tube arrangement, the voltages for the various dynodes are obtained from a series resistance voltage divider. In order to stabilize the photomultiplier tube gain, the current through the resistor string is made large compared to any average currents delivered by the photomultiplier tube collector. If the average current is on the order of 1 to 3×10^{-6} A, then the resistor current should be 1 to 3×10^{-4} A or larger. The net load presented to the power supply is, therefore, a constant resistance (within $\pm 1\%$) and the glow dis-

charge regulator will operate in an ideal manner.

It is of interest to consider the simplest type of stabilizer and to estimate the effect of the circuit parameters on the voltage stability or regulation. In fig. 2 we have shown schematically n tubes in series, which provide a voltage ne for the dynode resistor divider R_2 . The n tubes are supplied a current i_1 , from the unregulated voltage source E , through the current limiting

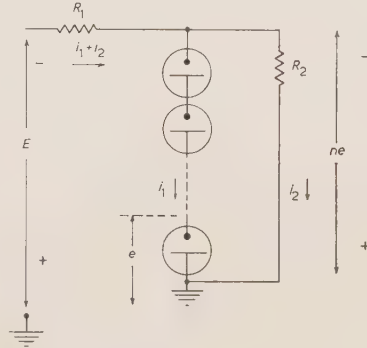


Fig. 2. Basic regulator circuit with n tubes in series.

resistor R_1 . The usual precautions, as noted by Benson on pages 30 to 33 of ref. 1), must be observed in choosing the circuit parameters in order that the tubes will initially "strike" and then operate in the correct current range. The voltage e across one tube can be approximately described for analytical purposes by linear function of the current through the tube:

$$e = a + bi_1. \quad (1)$$

A plot of e as a function of i , in the Mullard handbook³⁾, for the 85A2, yields the constants $a = 83.1$ V, $b = 300 \Omega$, for the operating range of 10^{-3} to 10^{-2} A.

Let us define the regulation factor M as

$$M = \frac{\delta E/E}{\delta(ne)/ne} = \frac{\text{relative variation of } E}{\text{relative variation of } ne}, \quad (2)$$

where δE is the variation of E and $\delta(ne)$ is the variation of ne .

For n tubes, the regulated voltage is $ne = n(a + bi_1)$;

$$\therefore \frac{\delta(ne)}{ne} = \frac{b}{e} \delta i_1. \quad (3)$$

⁷⁾ C. H. Townes, Theory of Cathode Sputtering in Low Voltage Gaseous Discharges, Phys. Rev. 65 (1944) 319.

⁸⁾ G. H. Rockwood, Current Rating and Life of Cold-Cathode Tubes, Trans. Am. Inst. Elec. Engrs. 60 (1941) 901.

Equation (3) demonstrates that the voltage stability is only slightly dependent upon the tube current. For example, for $i_1 = 2 \times 10^{-3}$ A,

$$\frac{\delta(ne)}{ne} = 7 \times 10^{-3} \left(\frac{\delta i_1}{i_1} \right).$$

If we neglect ageing and temperature effects, the variations δi_1 will be caused by the independent variations δE , δR_1 and δR_2 , and δi_1 may be computed by the propagation of error law. Thus

$$\delta i_1 = \pm \sqrt{\left(\frac{\partial i_1}{\partial E} \right)^2 (\delta E)^2 + \left(\frac{\partial i_1}{\partial R_1} \right)^2 (\delta R_1)^2 + \left(\frac{\partial i_1}{\partial R_2} \right)^2 (\delta R_2)^2}. \quad (4)$$

The current i_1 is derived from the two voltage loop equations for fig. 2, namely,

$$\begin{aligned} E &= R_1 (i_1 + i_2) + n(a + bi_1), \\ n(a + bi_1) &= i_2 R_2. \end{aligned} \quad (5)$$

Eliminating i_2 and solving for i_1 gives

$$i_1 = \frac{R_2 E - na(R_1 + R_2)}{R_1 R_2 + nb(R_1 + R_2)}. \quad (6)$$

Applying eq. (4) to eq. (6) yields a rather cumbersome expression for δi_1 :

$$\delta i_1 = \pm \frac{nR_1 R_2}{D^2} \sqrt{\left(\frac{D}{nR_1} \right)^2 (\delta E)^2 + \left[E \left(\frac{R_2}{n} + b \right) - aR_2 \right]^2 \left(\frac{\delta R_1}{R_1} \right)^2 + [Eb + aR_1]^2 \left(\frac{\delta R_2}{R_2} \right)^2}, \quad (7)$$

where $D = R_1 R_2 + nb(R_1 + R_2)$.

Fortunately, if the tube is to work as a regulator, it is required that R_1 and R_2 be large compared to the total dynamic resistance of the tubes, and eq. (7) may be simplified. That is,

$$\begin{aligned} R_1 &\gg nb, \\ R_2 &\gg nb. \end{aligned} \quad (8)$$

Therefore $D \approx R_1 R_2$,

$$\text{also } E \left(\frac{R_2}{n} + b \right) - aR_2 \approx \frac{R_2}{n} (E - na),$$

and $Eb + aR_1 \approx aR_1$

for reasonable values of E . With the approximation equation (8), eq. (7) reduces to

$$\delta i_1 = \pm \frac{1}{R_1}$$

$$\sqrt{(\delta E)^2 + (E - na)^2 \left(\frac{\delta R_1}{R_1} \right)^2 + \left(na \frac{R_1}{R_2} \right)^2 \left(\frac{\delta R_2}{R_2} \right)^2}.$$

If we let $(E - na) = kE$, where

$$0 < k < 1,$$

then

$$\delta i_1 = \pm \frac{E}{R_1} \sqrt{\left(\frac{\delta E}{E} \right)^2 + k^2 \left(\frac{\delta R_1}{R_1} \right)^2 + (1 - k)^2 \left(\frac{R_1}{R_2} \right)^2 \left(\frac{\delta R_2}{R_2} \right)^2}. \quad (9)$$

Equation (9) has its simplest form when $k = \frac{1}{2}$.

In a well designed power supply, one would try to equalize the terms under the square root sign. For the elementary circuit of fig. 2, when moderately stable resistors are used ($\delta R/R = \pm 10^{-3}$), the input voltage variation $\delta E/E$ will have the largest effect. Therefore

$$\delta i_1 = \pm \frac{\delta E}{R_1} \quad (9')$$

when

$$\frac{\delta R_1}{R_1} < \frac{\delta E}{E}, \quad \frac{\delta R_2}{R_2} < \frac{\delta E}{E}, \quad R_1 \approx R_2, \quad (10)$$

a result which could have been obtained easily by inspection of eq. (6) when conditions (8) and (10) are applied. The regulation factor M follows by combining eqs. (9'), (5), (3) and (2):

$$M = \frac{\delta E/E}{\delta(ne)/ne} = \left(1 - \frac{ne}{E} \right) \frac{e}{b} \left(\frac{1}{i_1 + i_2} \right). \quad (11)$$

In a practical power supply for 1700 V, it is interesting to evaluate M for various values of E . Let

$n = 20$ tubes (85A2),

$ne = 1700$ volts,

$i_2 = 0.2 \times 10^{-3}$ A = load current,

$i_1 = 2.0 \times 10^{-3}$ A = tube current,

$R_2 = \text{load resistor} \approx 8.5 \times 10^6 \Omega$.

Equation (11) is therefore

$$M = \left(1 - \frac{1700}{E} \right) 126.$$

A plot of M and the necessary resistance R_1 , as functions of E , is shown in fig. 3. When $E = \infty$, $M_{\max} = 126$. When $E = 2ne$, $M = \frac{1}{2} M_{\max} = 63$, and $k \approx \frac{1}{2}$ since $a \approx e$. When E is furnished by a simple high voltage rectifier unit, the relative variations of E will be the same as the relative variations in power line voltage. Suppose $\delta E/E = \pm 10\%$, corresponding to a line voltage of 115 ± 10 V a.c.; then for

$M = 63$, $\delta e/e = \pm 0.16\%$, and the photo-multiplier tube gain⁹⁾ would vary about $\pm 1\%$. If one needs more regulation, two stabilizers should be joined in series, with $2n$ tubes in the first, supplying $2ne$ volts for n tubes in the second. The combined regulation should be M^2 or about 4000. However, the best results from the compound stabilizer will be obtained only by controlling the temperature, recognizing

through a $1.5 \times 10^6 \Omega$, 10 W resistor. The regulated voltage is 1685 V and varies slightly from unit to unit. A circuit schematic is shown in fig. 4. It will be noticed that several additions have been made to the basic circuit (fig. 2) discussed above. Starting resistors, placed across most of the 85A2 tubes, reduce the necessary striking voltage for the 20 tubes in series to about $(1685 + 40)$ V; otherwise, with-

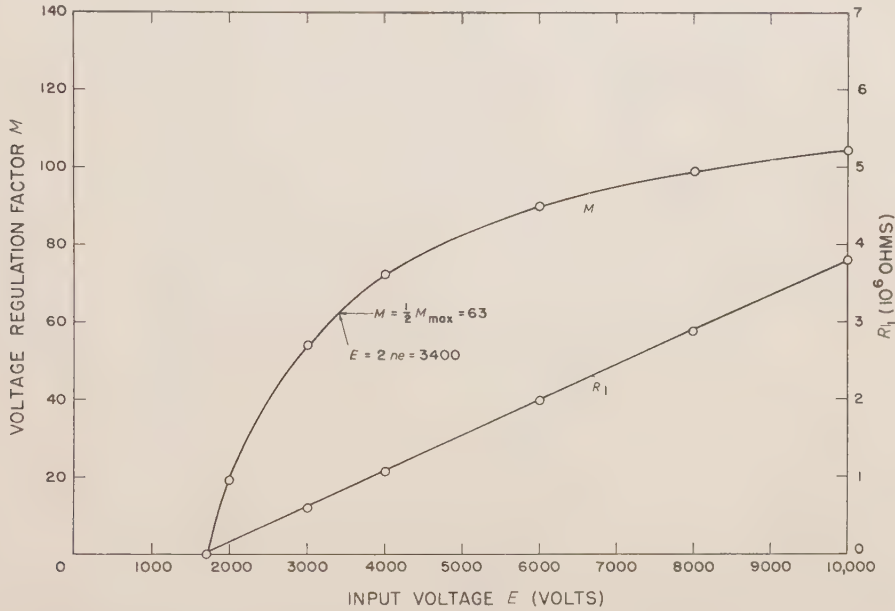


Fig. 3. Computed voltage regulation and series resistance R_1 for 1700 V output with twenty 85A2 tubes. Load resistance $= 8.5 \times 10^6 \Omega$. Limit for $E = \infty$. $M_{\max} = 126$.

the ageing phenomena, and using resistors of high stability. One example of a compound stabilizer has been built by J. K. Bair *et al.*¹⁰⁾.

5. Present Design

Using presently available parts, we have constructed a number of glow discharge tube regulated power supplies which operate photo-multiplier tubes with a 5×10^6 ohm dynode voltage divider. The supplies consist of a voltage source E rated at $E = 5400$ at 5×10^{-3} A (a packaged unit) feeding twenty 85A2 tubes

out the resistors, the striking voltage is about $(1685 + 500)$. As the voltage builds up across the tubes, first the open pair strike, then the pair across R_1 , then across R_2 , the process continuing until the last pair is reached when the tube across R_9 lights, then finally R_{10} . The capacitor C not only helps to reduce residual noise and rectifier ripple, but also limits the rate of voltage build up. When $C = 4 \times 10^{-6}$ farad, the short term fluctuations (< 1 second) are less than 10^{-3} volt. A measured regulation factor $M = 80$ agrees roughly with the results predicted by fig. 3. R_{11} , R_{12} and R_{13} should be good quality high voltage resistors. R_{12} protects the 85A2 from a current surge from C when the tubes initially strike. Resistor R_{13} protects the

⁹⁾ G. A. Morton, Photomultipliers for Scintillation Counting, RCA Rev. 10 (1949) 525.

¹⁰⁾ J. K. Bair *et al.*, An Extremely Stable Power Supply for Scintillation Counter Use, NEPA Division Report NEPA 1265-Ser-8 (January 20, 1950).

user of this supply from the energy stored in C . The high voltage at the output plug can be short circuited without damage to the circuitry.

A very rough attempt was made to measure the voltage drift of twenty 85A2 tubes in series, operating at 2 mA under constant current and temperature conditions. The average drift rate may have been as low as 10^{-5} V/h per tube over a period of 10 days. We concluded that operating

in the current literature. It has been demonstrated that the 85A2 tube has a very small voltage drift rate when operated at $\frac{1}{4}$ to $\frac{1}{5}$ its maximum rated current, and the question has been raised as to how stable the tube is and what its lifetime is at these reduced currents. The expected variations of the regulated voltage due to changes in line voltage and resistance variations in the circuit have been discussed.

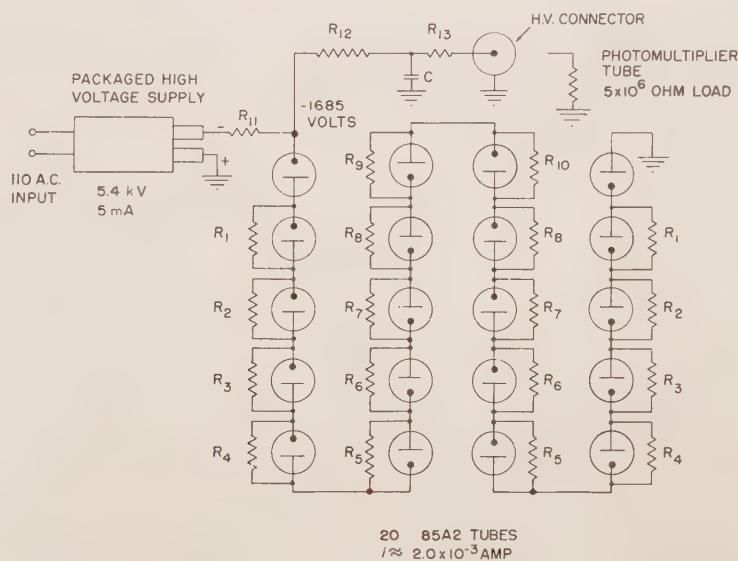


Fig. 4. Glow discharge regulator for photomultiplier tube voltage. $R_1 = 3.0$; $R_2 = 2.4$; $R_3 = 2.0$; $R_4 = 1.6$; $R_5 = 1.3$; $R_6 = 1.1$; $R_7 = 0.91$; $R_8 = 0.75$; $R_9 = 0.51$; $R_{10} = 0.39$; $R_{11} = 1.5$, 10 W; $R_{12} = 0.05$, 1 W; $R_{13} = 0.05$, 1 W; $C = 1$ to 4×10^{-6} F, 2000 V. Note: Resistance in $10^6 \Omega$. Resistors $\frac{1}{2}$ W except as noted.

the tubes at 2 mA instead of 8 mA definitely decreases the ageing rate, but quantitative results await better and more patient measurements.

6. Conclusions

These notes are intended as a guide to those who contemplate building regulated power supplies for use with photomultiplier tubes, or for those who have worried about the complexity and cost of some commercial power supplies for the same purpose. We have not said anything that is new, or that is not available

Finally, a practical circuit for regulating approximately 1700 V at about 0.1 to 0.2% for ordinary line voltage variations has been outlined.

Acknowledgments

The author wishes to express his appreciation to J. E. Allen for constructing a number of voltage regulated circuits and making preliminary tests, to W. H. Weber for valuable discussions of the merits of the glow discharge regulator, and to Mrs. Amie Smith for assistance in the writing of this paper.

AUTOMATIZATION OF PHOTOMETRIC MEASUREMENTS IN NUCLEAR EMULSIONS

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A device for the automatic focusing of tracks is described, based on an electromagnetic remote control objective. Furthermore, the measurement and recording of several

parameters related to the track's ionization are automatized. Time-gain, objectivity and greater precision are the main advantages of the system.

1. Introduction

It is well known that ionization measurements in nuclear emulsions are strongly subjective, especially when the specific energy loss is rather high. A method widely used during the past years in order to eliminate this drawback—especially in the case of particles with $Z > 1$ —is that of the photometric measurements^{1–5}).

This method, however, still involves a personal factor in the focusing of the track. Added to the fluctuations, this fact reduces the possibility of discrimination between particles of slightly different Z .

Within the framework of the automatization investigations carried out in our laboratory^{6–9}) concerning scanning and measurement operations in emulsions, we have constructed a device capable of automatically focusing the track, coupled to a conventional photometric system of the rotating prism type. We have furthermore automatized the measurement and recording of the various parameters characterizing a particle's ionization. This combination of automatized operations allows (1) a better reproducibility of the results and (2) a time gain,

due both to the greater velocity with which the single operations are performed and to the possibility of simultaneously obtaining the various parameters of interest.

2. Operating Principle

2.1. AUTOMATIC FOCUSING

The objective is mounted on an iron membrane attracted by an electromagnet. The manual focusing operation is thus substituted by the control of the current passing through the electromagnet's coil. This control is carried out by means of the pulse generated by the track, through a maximizing operation.

Let the track be within 50 microns (maximum focusing range allowed by the electromagnetic objective) underneath the optical object plane; the corresponding peak amplitude of the pulse given by the photometric apparatus will be the smaller, the further away the track is from perfect focus. The maximum value of the peak amplitude will correspond to the perfect focusing of the track.

The diagram in fig. 1 shows how the output of the photomultiplier is handled. As is known, the output consists of a square wave generated by

¹) G. Kayas and D. Morellet, *Compt. Rend. Ac. Sci.* **234** (1953) 1359.

²) L. Van Rossum, *Compt. Rend. Ac. Sci.* **266** (1953) 2234.

³) S. Von Friesen and K. Kristiansson, *Arkiv f. Fys.* **4** (1953) 505.

⁴) M. Della Corte, *Nuovo Cimento* **4** (1956) 1565.

⁵) M. Artom and C. Gentile, *Suppl. Nuovo Cimento* **2** (1956) 254.

⁶) G. Baroni and C. Castagnoli, *Suppl. Nuovo Cimento* **2** (1954) 364.

⁷) E. Amaldi, C. Castagnoli and C. Franzinetti, *Nuovo Cimento* **4** (1956) 1165.

⁸) C. Castagnoli, M. Ferro-Luzzi and C. Franzinetti, *Atti del Congresso di Padova-Venezia* (1957)

⁹) C. Castagnoli, M. Ferro-Luzzi and M. Muchnik, *Nuovo Cimento* **8** (1958) 936.

low impedance path for the positive pulses when is not cut off by the triangular negative pulse on its grid. T_4 acts as a d.c. restorer and T_5 as the output cathode-follower.

In the automatic focusing circuit (fig. 3) a

means of the low grid-current amplifier T_{13} – T_{14} and thus the mechanical lifting of the objective.

As far as the carrying out of the operations is concerned, it is to be noted that a fluctuation is superposed on the regular peak value of the

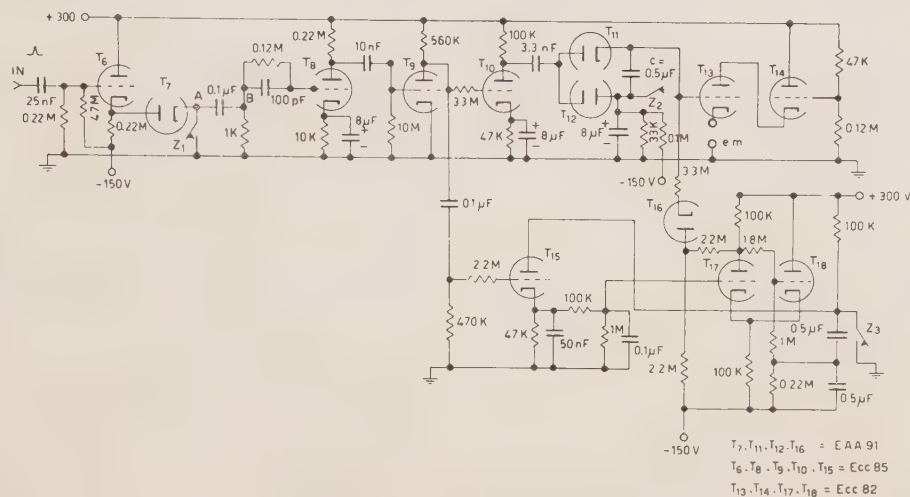


Fig. 3. Automatic focus circuit.

stepwise wave form whose height equals that of the last pulse is generated at A; at B the peak voltage of the pulses is proportional to the increase in height from one pulse to the next (time derivative). T_8 and T_9 strongly amplify and equalize those derivative pulses of height greater than a given adequately fixed value.

The portion corresponding to block B_1 in fig. 1 consists of flip-flop T_{17} – T_{18} which charges, through diode T_{16} , condenser C hence pulling up the objective (through T_{13} – T_{14} which represent the block under the heading “coil excitation control” in fig. 1), and finally increasing the pulse amplitude. This takes place till the time derivative of the pulse height reaches a value sufficient to start the operation in block B_2 . At that point the derivatives coming from T_9 see that the flip-flop is reversed and the charging up of C through T_{16} is stopped. At that moment block B_2 is already working and T_{10} transmits, through T_{11} , the derivative pulses to condenser C, further increasing its charge till the derivative goes to zero, corresponding to the perfect focus of the track. The voltage of C regulates the current flowing in the electromagnet’s coil by

pulses originating in mechanical vibrations, photomultiplier background, etc. This fluctuation noise tends to interfere with the normal operation of the circuit, since a necessary condition for focusing is that the derivative be always positive. In order to eliminate the effects of this fluctuation (1) the coupling time constants have been reduced to a minimum so as to reduce the slow component of the noise, (2) the reversal of the flip-flop is controlled by means of lengthened integrated pulses with a time constant such as to average over a number of successive pulses.

2.2. AUTOMATIC MEASUREMENTS

As it is well known¹), depending on the various ionization regions, it may be useful to consider the height h of the pulse, or the width λ or still the integral S . We do not know of any systematic study having the scope of establishing the best parameter for each particular case. To make such a study feasible and in any case to extract the maximum amount of information on the track, we have completed a device capable of simultaneously measuring all three quantities.

The circuit is shown in fig. 6. Double-diode T_{39} - T_{40} furnishes a rectified voltage equal to the peak-to-peak amplitude of the square wave signal; this voltage is compared, by means of R_1 , with a reference voltage adjustable by potentiometer R_2 . The error voltage, applied to the grid of T_{42} , is then amplified and fed back into the photomultiplier's d.c. supply.

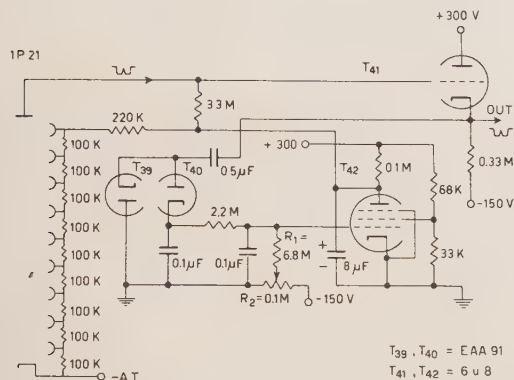


Fig. 6. Sensitivity stabilizer circuit.

2.4. OPERATION

Once the track is positioned under the microscope, all operations take place automatically as soon as a switch is closed. A programming unit (fig. 1) consisting of a motor making one revolution in 15 seconds, close one after the other the contacts which start the various operations: (1) the focusing operation is started, by reversal of the flip-flop in fig. 3, (2) after a sufficiently long time so that perfect focus is achieved, the pulse is sent to the various measuring units, (3) the measured voltages are digitized, (4) the number are printed on paper tape, (5) the whole system is reset and the programming unit stops.

3. Measurements and Advantages of the Present Method

3.1. FOCUSING

In order to check the reproducibility of the automatic focusing, the height of the pulse generated by an oxygen track in G5 emulsion and seen through a slit of dimensions 20 microns $\times$ 0.2 microns in the image plane, was measured (fig. 7). The measurements correspond always to

the same portion of the track. It is clearly seen how the distribution has a larger spread in the case of manual-visual focusing than in the

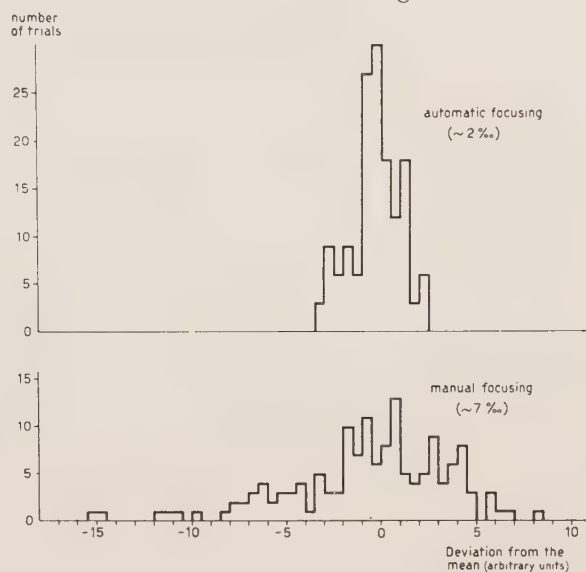


Fig. 7. Automatic and manual focusing distributions.

automatic focusing case. It is interesting to compare the spread of the automatic measurements with that of the manual ones carried out by an average scanner in given time limits. Fig. 8 shows the root mean square deviation μ as a function of the time Δt available for the

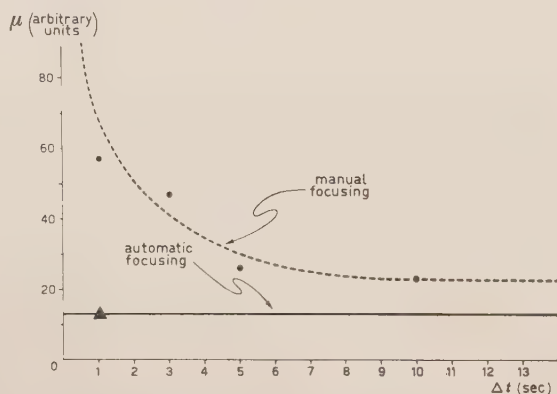


Fig. 8. Time dependence of the errors.

manual focusing; it is assumed that the value corresponding to $\Delta t = 10$ seconds is a lower limit for the manual focusing spread. Indeed, for longer times the fluctuations of the pulses to be measured begin to bear on the overall

precision (heating of the emulsion, etc.). The automatic focusing μ is to be compared with the manual value at 1 second; it is to be noted that normally the manual operation requires at least 5 seconds.

3.2. MEASUREMENT TIME

It may be subdivided into: (1) time needed to align the given portion of track under the microscope objective; it varies according to the type of measurement to be performed, to the slit being used, and to the required precision of the positioning; for portions of track in succession along the same track, an average slit length of 20 microns, and a rather small precision on the range, the track may be translated without actually looking into the microscope and using instead the external coordinates of the stage; in this case, a few seconds are enough to complete this operation; (2) time needed to align the track to the slit; if an Amici prism is used in order to rotate the image, and if the parallelism is controlled on the image of the track pulse seen at the oscilloscope, the operation may be performed in a few seconds; (3) time needed to focus the track and perform the required measurements; in our case 15 seconds are needed in order to measure all three parameters h , λ , S and their transcription onto paper tape.

3.3. SELECTION OF THE BEST PARAMETER

Heavy ion tracks have been measured (carbon, nitrogen, oxygen, neon and argon) in G5 emulsions exposed at Berkeley. The particles had an initial energy of 10 MeV per nucleon.

The measurements were performed with a slit of 20 microns $\times$ 0.2 microns ($50 \times$ objective, $25 \times$ eye-piece). Each track was measured just once and at a single range value, after entering the emulsion, corresponding to a $\bar{\beta} = 0.127$. The results plotted on logarithmic scale, are seen in fig. 9. Each point corresponds to the mean of 10 tracks. From this research the indication may be extracted that the most sensitive parameter for this type of measurement is the integral S .

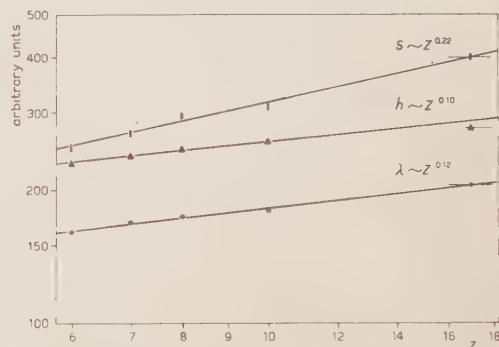


Fig. 9. Z dependence of the track parameters. Standard deviations are of the order of magnitude of the points.

To conclude we can say that the advantages of the present method are the following: (1) a higher precision in the single measurement and a consequent higher sensitivity of the photometric method; (2) a time gain in the measurements and in their transcription; (3) a considerable reduction of the observer's fatigue.

Acknowledgements

Thanks are due to Prof. W. H. Barkas for kindly lending us the plates exposed to the HILAC at Berkeley.

EINE MÖGLICHKEIT DER STROMINTENSITÄTS- UND ENERGIEERHÖHUNG DES MIKROTRONS

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The energy gain during the first crossing of the accelerating gap of the microtron resonator, and the transition of the electrons into phase stable region are investigated. It is shown that for proper operation of the X-band microtron the accelerating gap should not be greater than 3 mm. A

modification of the S-band microtron is proposed. Using a magnetic field of 4400 gauss and a peak voltage of 2.3 MV across an accelerating gap of 21 mm it seems possible to obtain a four times greater energy at the same diameter of the magnet than with the microtrons built so far.

1. Einführung

Beim Mikrotron gewinnt man zumeist die Elektronen mittels Feldemission¹⁾ oder neuerdings²⁾ mittels Elektroneneinspritzkanone. Bei der Hendersonschen Ausführung wurde die Beschleunigungsstrecke möglichst kurz gewählt (7.8 mm), damit die Laufzeiteffekte der ersten Beschleunigung möglichst klein sind. Die meisten Elektronen, die im Augenblick der grössten Feldstärke an der Kathode starten, durchlaufen das nächste Mal die Beschleunigungsstrecke des Resonators in phasenstabiler Lage³⁾. Sedlaček und Wernholm²⁾ hatten mittels Einspritzkanone den geringeren Gewinn bei der ersten Durchquerung des Beschleunigungspaltes kompensiert.

Jeder von diesen Vorschlägen ist beim S-Band ($\lambda = 10$ cm) realisierbar, versagt aber beim X-Band ($\lambda = 3$ cm) Mikrotron. Für die Anbringung einer Einspritzkanone würde kaum Platz zu finden sein. Wollte man bei einer Beschleunigung die gleiche Energie gewinnen wie beim S-Band Mikrotron, so müsste der Spalt — den Laufzeiteffekten entsprechend — im Verhältnis der Wellenlängen verkleinert werden. Beim

Betrieb $a = 2$, $b = 1$ müsste demnach der Spalt etwa 2.5 mm betragen. (a ist die Zahl der Hochfrequenzperioden τ beim ersten Umlauf und $a + (n - 1)b$ die Zahl beim n -ten Umlauf.) Die Strecke von 2.5 mm würde kaum eine Spannung von 600 kV aushalten. Gehen wir aber auf den Betrieb $a = 3$, $b = 1$ wie bei Kaiser⁴⁾, so müsste die Beschleunigungsstrecke noch kürzer gewählt werden.

Im folgenden werden wir die erste Beschleunigung als Einspritzung für die nächste Beschleunigung betrachten. Hierbei wird es notwendig sein nicht nur die Energieverhältnisse, sondern auch die Phasenverschiebung der ersten Beschleunigung zu berücksichtigen. Es wird sich zeigen dass es möglich wäre, ein S-Band Mikrotron zu bauen, bei dem das magnetische Feld und die Spannungsamplitude etwa viermal erhöht werden. Damit wird beim gleichen Durchmesser des Magneten die Endenergie etwa viermal vergrössert.

2. Berechnungen

Wenn die Elektronen durch Feldemission und nicht mittels einer Warmkathode gewonnen werden, so wird der grösste Teil im Augenblick der maximalen Feldstärke emittiert. Beim Verändern der Feldstärke um nur 10% verkleinert sich die Zahl der austretenden Elektronen um eine bis zwei Grössenordnungen⁵⁾. So wollen

¹⁾ C. Henderson, F. F. Heyman und R. E. Jennings, Proc. Phys. Soc. B 66 (1953) 654.

²⁾ M. Sedlaček und O. Wernholm, Privatmitteilung.

³⁾ C. Henderson, F. F. Heymann und R. E. Jennings, Proc. Phys. Soc. B 66 (1953) 41.

⁴⁾ H. F. Kaiser und W. T. Mayes, Rev. Sci. Instr. 26 (1955) 565.

wir bei den folgenden Berechnungen annehmen, dass die Elektronen an der Kathode im Augenblick der grössten Spannung starten. Ferner sollen die Elektronen den Spalt in dem Augenblick verlassen, wo die elektrische Feldstärke E auf Null sinkt. Damit soll es möglich sein, eine möglichst lange Beschleunigungsstrecke zu wählen, um die Durchschlagsgefahr möglichst klein zu halten und um eine hohe Güte des Hohlraumresonators zu erreichen. Beim nächsten Durchgang sollen gerade diese Elektronen zur Zeit der Resonanzphase⁶⁾ φ_r die Mitte der Beschleunigungsstrecke durchqueren. Im Folgenden wollen wir nach den erwähnten Gesichtspunkten die optimale Länge des Beschleunigungsspaltes L , die Amplitude der Beschleunigungsspannung U und die magnetische Flussdichte B des homogenen Magnetfeldes für verschiedene technisch interessante Resonanzbedingungen ermitteln.

Nehmen wir ein homogenes Beschleunigungsfeld $E = (U/L) \cos \omega t$ an und berücksichtigen wir nicht die Bahnkrümmung, die das Magnetfeld im Spalt bewirkt. Die Beschleunigungsspannung soll so gross sein, dass wir bei der zweiten und den weiteren Beschleunigungen mit $\beta = v/c = 1$ rechnen können.

Die Energie W eines Elektrons, dass sich im erwähnten elektrischen Felde bewegt, verändert sich wie folgt:

$$\frac{dW}{dt} = ec \frac{U}{L} \beta \cos \omega t. \quad (1)$$

Mit Hilfe von

$$dW = W_0 \frac{\beta}{(1 - \beta^2)^{\frac{3}{2}}} d\beta, \quad W_0 = m_0 c^2, \quad (2)$$

wobei m_0 die Ruhemasse ist, finden wir für die oben festgesetzten Anfangsbedingungen $t_1 = 0$, $\beta_1 = 0$:

$$\beta = \left(\frac{A^2 \sin^2 \omega t}{1 + A^2 \sin^2 \omega t} \right)^{\frac{1}{2}}, \quad A = \frac{e}{2\pi W_0} \frac{U\lambda}{L}. \quad (3)$$

Hieraus folgt für die als günstig angenommene Austrittszeit ($\omega t_2 = \frac{1}{2}\pi$) die Endgeschwindigkeit

$$\beta_2 = \left(\frac{A^2}{1 + A^2} \right)^{\frac{1}{2}} \quad (3a)$$

$$\text{und wegen} \quad \int_0^{t_2} \beta dt = \frac{L}{c} \quad (4)$$

die Bedingung für die entsprechende Länge L der Beschleunigungsstrecke

$$\frac{e}{2\pi W_0} \frac{U}{L} = \operatorname{tg} 2\pi l, \quad l = \frac{L}{\lambda}. \quad (5)$$

Bei der zweiten und weiteren Beschleunigungen gewinnt das Resonanzelektron die Energie³⁾

$$\Delta W_r = eU \frac{\sin l\pi}{l\pi} \cos \varphi_r, \quad (6)$$

bei der ersten aber etwas weniger:

$$\Delta W_1 = k \Delta W_r, \quad 0 < k < 1. \quad (7)$$

Mit (3a) ergibt sich:

$$W_0 + k \Delta W_r = W_0 (1 - \beta_2^2)^{-\frac{1}{2}} = W_0 (1 + A^2)^{\frac{1}{2}}. \quad (8)$$

Berücksichtigen wir, dass das Elektron den Spalt nicht wie bei der zweiten und folgenden Beschleunigungen zur Zeit $(\varphi_r/2\pi)\tau + L/2c$, sondern zur Zeit $\frac{1}{4}\tau$ verlässt. So ist die Zeit T_1 , die für die erste Bahn verbraucht werden soll, gerechnet von der Mitte des Spaltes, nicht genau $T_1 = a\tau$, sondern

$$T_1 = a\tau - p\tau, \quad p = \frac{1}{4} - \frac{1}{2}l - \frac{\varphi_r}{2\pi}. \quad (9)$$

Aus den bekannten Relationen für die Resonanzelektronen⁷⁾

$$T_1 = \frac{2\pi W_0 + k \Delta W_r}{ec^2 B} \quad (10)$$

und

$$T_{n+1} - T_n = \Delta T = \frac{2\pi \Delta W_r}{ec^2 B} = b\tau \quad (11)$$

folgt mit (9):

$$\Delta W_r = \frac{b}{a - p - bk} W_0. \quad (12)$$

Wie bis jetzt noch in allen Ausführungen nehmen auch wir $b = 1$; so folgt mit den Gleichungen (6), (8) und (12)

$$U = \frac{W_0}{e} \frac{1}{\cos \varphi_r} \frac{(1 + A^2)^{\frac{1}{2}}}{a - p} \frac{l\pi}{\sin l\pi}. \quad (13)$$

Durch Einsetzen der Gleichung (5) resultiert

$$2 \cos \varphi_r (a - p) = \frac{1}{\sin l\pi \sin l2\pi}. \quad (14)$$

⁵⁾ Vgl. z.B.: M. Ardenne, Tabellen der Elektronenphysik Ionenphysik und Uebermikroskopie.

⁶⁾ C. Schmelzer, Z. Naturforschg. 7a (1952) 808.

⁷⁾ P. A. Redhead, H. LeCaine und W. J. Henderson, Can. J. Research A 28 (1950) 73.

Aus den Gleichungen (14), (13), (12) und (11) sind einige Data für die Fälle $\varphi_r = 18^\circ$, $b = 1$ und $a = 1, 2, 3, 4$, berechnet und in der Tabelle 1 zusammengestellt worden. Der Durchmesser D_1 der ersten Elektronenbahn folgt aus der Gleichung⁷⁾

$$D_1 = 2 \frac{[(W_0 + k\Delta W_r)^2 - W_0^2]^{\frac{1}{2}}}{ecB}.$$

(15)

den ersten Elektronenstrahl im Resonator selbst kreisen zu lassen (Abb. 1) und ihn dann durch ein kleines Loch durchzulassen. Man müsste noch berücksichtigen, dass das Elektron in der Beschleunigungsstrecke nicht die volle Energie $k\Delta W_r$ gewinnt und dass auch das Magnetfeld des Resonators nicht zu vernachlässigen ist. Beim Resonator der Abbildung 1

TABELLE 1

		S-Band ($\lambda = 10$ cm)			X-Band ($\lambda = 3$ cm)		
a	U (MV)	B (gauss)	D_1 (mm)	L (mm)	B (gauss)	D_1 (mm)	L (mm)
1	2.369	4398	27.7	20.7	14 660	8.3	6.2
2	0.427	828	42.8	12.8	2 761	12.8	3.6
3	0.238	473	53.0	10.1	1 573	15.9	3.0
4	0.165	325	62.6	8.6	1 083	18.8	2.6

3. Schlussfolgerungen

Aus der Tabelle 1 ersehen wir, dass bei einem X-Band Mikrotron die Beschleunigungsstrecke mit $a = 3$ nicht länger als 3 mm sein sollte. Da die bis jetzt gebauten X-Band Mikrotrone Beschleunigungsspalte von etwa 4.5 mm und mehr hatten, ist es zu verstehen, warum die Intensität des Elektronenstromes mit wachsendem Radius so stark abnimmt. Es starten zwar einige Elektronen, bevor die Spannung im Resonator die volle amplitude erreicht hat und kommen beim nächsten Durchgang in den Beschleunigungsprozess. Die meisten Elektronen kommen jedoch bei zu langer Beschleunigungsstrecke nicht in die phasenstabile Lage und gehen schon nach einigen Umläufen verloren.

Vielleicht wären die Werte der Tabelle 1 für das S-Band für den Fall $a = 1$ (nicht mehr $a = 2$ wie bisher!) einer Beachtung wert. Das magnetische Feld und somit ΔW_r sollten für die Resonanzbedingungen etwa viermal erhöht werden. Man erhielte somit beim gleichen Durchmesser des Magneten eine etwa viermal grössere Energie. Der Durchmesser der ersten Bahn betrüge dabei jedoch nur 28 mm, während selbst die Beschleunigungsstrecke 21 mm lang sein würde. Es könnte vielleicht möglich sein,

ist das zeitliche und räumliche Maximum der magnetischen Flussdichte kleiner als $E_{\max}/c \approx 3400$ gauss. Ausserdem würde das Elektron nach der Umkehrung der Bahn wegen der Umkehrung des elektrischen Feldes noch eine zusätzliche Beschleunigung erfahren. Wenn wir für das Herauslassen des Elektronenstrahles ein Loch benützen, sollte die Wand nicht zu dünn sein, damit die Güte des Resonators nicht zu

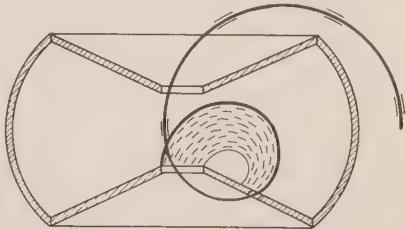


Abb. 1. Schematische Darstellung eines Resonators für ein S-Band Mikrotron für den Fall $a = 1$. Die Elektronen, die am linken Spaltrand entspringen, verlassen den Resonator durch die Öffnung an der rechten Seite; die übrigen Elektronen gehen verloren.

viel leidet. Oder man sollte die Elektronen durch eine dünne Silbermembran durchlassen. Was die Durchschlagsgefahr in der Beschleunigungsstrecke betrifft, sei zu erwähnen, dass dieselbe sehr verkleinert würde, da die Elektronen nicht

auf die der Kathode gegenüberliegenden Seite anstossen, sondern schon früher umkehren würden. Da in den Beschleunigungsprozess vor allem die Elektronen gelangen, die an einer Seite (links in der Abbildung 1) starten, wäre es angebracht, die Feldemission an allen übrigen Teilen des Spaltrandes etwa durch Vergolden und sorgfältiges Polieren zu unterdrücken, damit der Resonator nicht unnütz belastet wird. Nur an der Stelle, wo wir Elektronen wünschen, sollte man die Austrittsarbeit herabsetzen oder durch Anrauen der Oberfläche das lokale elektrische Feld erhöhen. Damit könnte man vielleicht eine recht bedeutende Vergrößerung des Elektronenstromes erzielen. Bei genauerer Untersuchung könnte es sich zeigen, dass die Elektronen nicht in optimaler Richtung zur zweiten Beschleunigung zurückkehrten. Die

erste Bahn könnte dann durch ein kleines magnetisches oder elektrostatisches Feld korrigiert werden.

Aitken und Jennings berichten über ein S-Band Mikrotron von 29 MeV und einem Durchmesser von etwa 2 m⁸). Wenn es gelänge, ein S-Band Mikrotron nach dem oben beschriebenen Prinzip zu bauen, so würde bei demselben Durchmesser eine Endenergie von über 100 MeV erreicht werden, ohne etwas an den übrigen Vorteilen des Mikrotrons, unter anderem der leichten Herausführung und der Homogenität des Elektronenstrahles, zu verlieren.

Zum Schluss möchte ich herzlichst den Herren Dr. I. Kuščer und Dr. S. Poberaj für nützliche Diskussionen danken.

⁸) D. Aitken und R. E. Jennings, *Nature* **181** (1958) 1726.

A PROPORTIONAL COUNTER FOR LOW LEVEL COUNTING WITH HIGH EFFICIENCY

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Two small nearly identical counters have been built in the C^{14} dating laboratories in Groningen and Uppsala, from essentially the same material. The counting space is lined with quartz covered with a conducting layer; it is enclosed

in a copper cylinder at ground potential. The backgrounds are 1.33 and 0.9 cpm. The total volumes are 0.55 l with efficient volumes of about 0.46 l.

1. Introduction

Very often the amount of material provided by archaeologists and geologists for C^{14} dating purposes is limited. It is therefore of great value if the ineffective volume of the counter is as small as possible. Furthermore a low background is similarly important. For routine dating work it is also of great value if the sample size can be reduced since then the time for the combustion and purification of the samples will be shorter. As material, facing the counting volume, quartz was chosen, since it showed a very low radioactive contamination in a counter constructed a few years before^{1,2}). The construction was changed however, in order to get the ineffective volume as small as possible. Moreover in the new design the quartz is enclosed in a copper tube, which will stand higher pressures. Another advantage is that this copper tube is at ground potential, and acts as a Faraday cage.

2. Construction of the Counters

2.1. THE QUARTZ TUBE

The tube (see fig. 1) consists of transparent quartz with a total length of 349 mm. Two annular quartz end plates, C (thickness 5 mm),

are melted on to the inside of the quartz tube. The distances from the surface of the end plates to the ends of the tube are 13.7 mm. The inner diameter of the quartz tube is 44.6 ± 0.1 mm and that of the hole in the end plate 22.2 mm. The wall thickness of the tube is about 3.0 mm. The whole surface except the surfaces from the copper flanges in the end plates to the ends of the tube, is coated with a (transparent) layer of tin oxide to get a conducting surface. The high voltage is applied to the inner wall of the quartz tube.

2.2. THE COPPER TUBE

The quartz tube is put into a copper tube, slightly longer than the quartz tube, having copper endplates. The plate E supports all the connections.

The counter shown in fig. 1a has teflon O-rings, L and M, between the copper tube ends and each of the plates E and F. There is a brass ring silver soldered on each end of the copper tube. On these rings two annular iron nuts, J and K, are screwed; then the plates are pressed

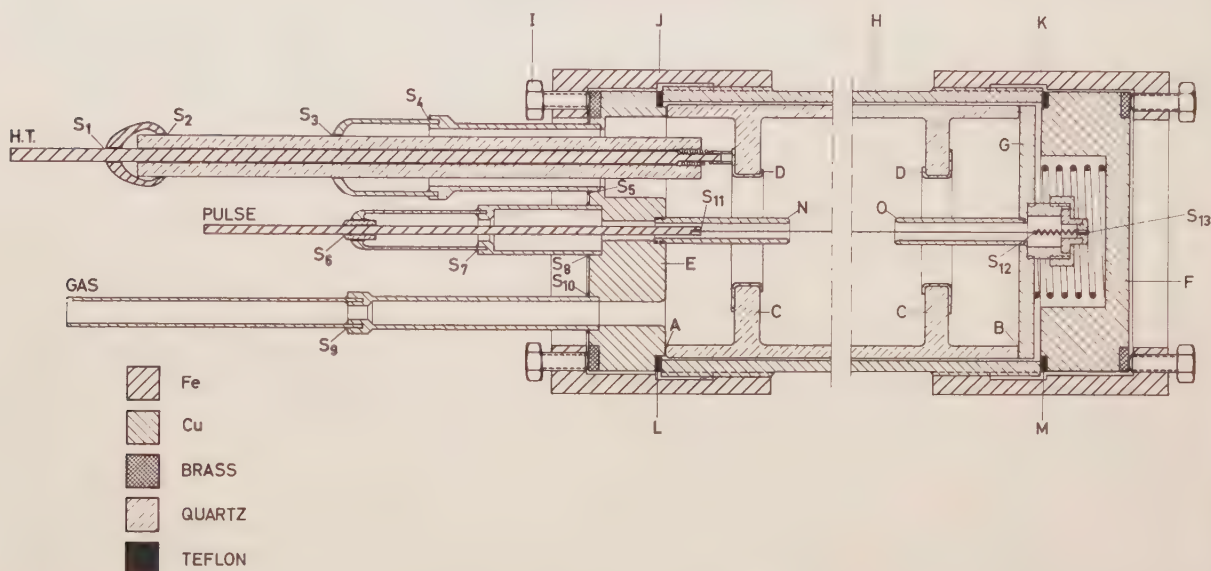
¹) G. W. Barendsen, Ouderdomsbepaling met radioactieve koolstof, Thesis, Groningen (1955).

²) Hl. de Vries, Nuclear Physics 3 (1957) 65.

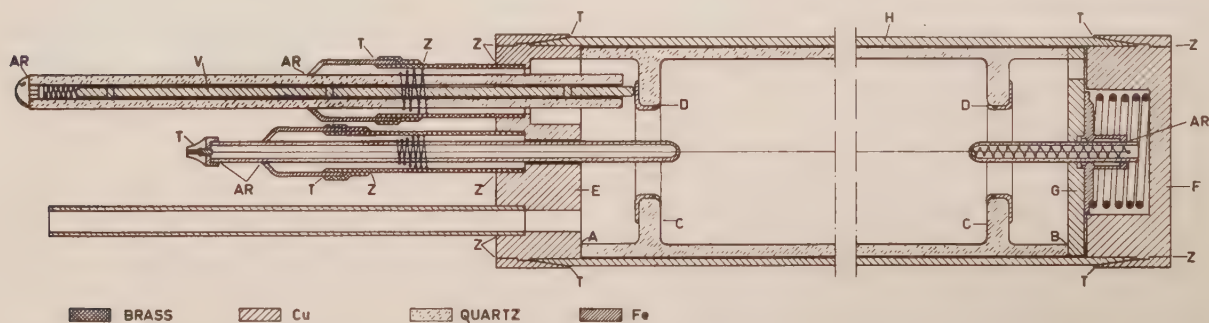
more firmly against the teflon with six screws, I, at each end of the counter. This seal has been very good. The counter was designed to stand a

The counter used in Groningen was built from the same batch of quartz and copper. In order to enable experiments in an (annular) anti-

Fig. 1. THE COUNTER



1a. *Upper drawing: Uppsala counter.* AB is a quartz tube with two flanges C. It is covered with tin oxide except the surfaces from the copper flanged rings D, to the ends of the quartz tube. All insulators are quartz. H is a copper tube, which, together with the copper plates E and F, constitutes a pressure and vacuum tight enclosure for the counter. J and K are steel nuts which are screwed on to keep the end plates on place. Screws I give the final pressure on the copper end plate. L and M are teflon O-rings between the tube and the plates. N and O are the ends of two copper guard tubes. S₁, S₄, S₇, S₉, S₁₁, S₁₂ and S₁₃ are tin solderings; S₅, S₈ and S₁₀ are silver solderings; S₂, S₃ and S₆ are araldite seals. The high voltage is put on the cathode via an iron bar (H.T.). The copper enclosure is on ground potential.



1b. *Lower drawing: Groningen counter.* Main differences are: The endplates E and F are tin soldered on the copper tube H. The guard tubes which define the effective lengths are made out of quartz. The high voltage supply also is somewhat different. (See drawing). Z are silver solderings. T are tin solderings. AR are araldite seals.

high pressure, but has not yet been tested at a higher pressure than 3 atm. A similar teflon seal has been used previously³⁾.

³⁾ W. H. Burke and W. G. Meinschein, Rev. Sci. Instr. 26 (1955) 1137.

coincidence ring, already built, the thicker rings at the ends had to be avoided. Therefore the end plates were soldered on as shown in fig. 1b. A tin solder was used, mixed from pure tin and old (inactive) lead.

2.3. THE HIGH VOLTAGE SUPPLY

The high voltage is fed to the wall via an iron bar insulated from the copper by another quartz tube (see fig. 1). To get a good contact between the bar and the tin oxide on the quartz endplate a flanged ring was pressed into the hole in the endplate. Moreover this ring protects the tin oxide in case of a strong discharge which could occur if the gas would be pumped out without reducing the voltage on the counter.

2.4. THE WIRE AND THE GUARD TUBES

To keep the main quartz tube in place there is a copper plate, G, pressed to the end B of the quartz tube by a spring in the cavity of the end plate F. This plate also supports one end of the wire.

The wires are made of stainless steel, 0.05 mm $\varnothing$. The guard tubes are made of copper (Uppsala) or quartz covered with tin oxide (Groningen). The unshielded part of the wire (between N and O), is 300 mm (306 mm in Groningen). The guard tubes reach 5.7 mm (3.0 mm in Groningen) into the counting volume. This is a very essential detail. If the guard tube is made longer, the effective volume will be reduced. If, however, this tube is too short, or if it would end in a conical tip, the field at the two ends of the wire would be stronger than over its main (central) part. Consequently the counter might "break down" at the ends at a voltage optimal for operation of the central part of the wire. The value of 3.0 was the best compromise between these two extremes.

Various calculations and experiments on a model have been used for finding this optimum value. Partly they have been mentioned already at the C¹⁴ Conference in Copenhagen 1954; they will be published in the near future⁴).

2.5. THE GAS INLET

The gas inlet is a copper tube about 5 mm i.d.

Some scratches at the end surface of the quartz tube permit the gas to go into or to be pumped away from the space between the copper and quartz tubes.

2.6. THE MATERIAL

All material (quartz, copper tube, end plates, were from one tube, bar etc.). The only material from a different supply is the central wire and the guard tubes (copper in Uppsala, quartz in Groningen), and the copper flanges in the end plates. The tin oxide was sprayed on the quartz at the same time in Groningen.

3. Counterperformance

3.1. END EFFECTS

The end effects have been reduced with a suitable arrangement of high voltage on the end surface as well as on the walls of the counter and a rather wide guard tube at ground potential. From the model experiments⁴), we can estimate the end effects to reduce the counting rate with $(2.8 \pm 1.5\%)$ of the total counting rate for C¹⁴. For the Groningen counter this reduction would be about $2 \pm 1.5\%$.

3.2. THE EFFECTIVE VOLUME

From the end effects mentioned above (1.3.1) and wall effects the effective volume can be calculated and is approximately equal to the volume of the cylinder between the ends of the guard tubes. It is 85% of the total volume.

3.3. RECENT CARBON

The counting rate for 1 g recent carbon, calculated from the efficiency data given, is 13.4 c.p.m. for the Uppsala reference sample.

3.4. THE BACKGROUND

The background is for the Uppsala counter: at 3 atm CO₂ and barometric pressure 745 mm 0.95 c.p.m., variation — 0.035, with probable error ± 0.010 , c.p.m./10 mm barometric pressure; at 2 atm CO₂ and barometric pressure 735 mm 0.90 ± 0.03 c.p.m.; at 1 atm CO₂ and barometric pressure 753 mm 0.84 ± 0.03 c.p.m. In Groningen the background is 1.33 c.p.m. at 3 atm. In Uppsala the length of the anti-coincidence ring is much larger than in Groningen. In Uppsala some background measurements were made in which the proportional counter

⁴) Hl. de Vries, in preparation.

was displaced towards the end of the A.C. ring. These measurements indicate that the higher background in Groningen is probably due to mesons escaping from the ends of the A.C. ring.

The alpha's give a contribution to the background of about 0.17 c.p.m. included in the figures above. Alpha's mean what is counted in the channels with a higher threshold. The threshold was adjusted so that 1 per cent of the C^{14} -beta's were recorded in this channel.

The shields are described elsewhere^{2,5)}.

The background of the Uppsala counter

without any mercury in the tank was 2.05 ± 0.03 c.p.m. at a barometric pressure of 762 mm Hg.

Acknowledgements

One of us (I. O.) wants to express her gratitude to Ministerie van Onderwijs, Kunsten en Wetenschappen for giving her a scholarship in collaboration with Svenska Institutet, Stockholm. The scholarship made it possible for her to work on the counter in Groningen.

⁵⁾ I. Olsson, Arkiv för Fysik **13** (1958) 37.

EIN ELEKTRONISCHES KOINZIDENZVERFAHREN HOHER AUFLÖSUNG†

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Eingegangen am 25. April 1959

An electronical coincidence-method is described, which has a time resolution of 7×10^{-12} sec with artificial pulses. The statistical error of the apparatus was calculated and its agreement with the experimental data is stated. The

calibration was performed with a variable delay line and the linearity of the relation between pulse-height and time delay was proved within a range of 2×10^{-9} sec.

Das Auflösungsvermögen einer schnellen Koinzidenzapparatur wird bekanntlich bestimmt durch die Genauigkeit, mit der der Zeitpunkt des Durchgangs eines Teilchens durch einen der beiden Zähler von der gesamten Apparatur fixiert werden kann. Der Gesamtfehler einer solchen Anordnung entsteht dabei durch Überlagerung aller durch die Apparatur implizierten Einzelfehler.

Zur Verbesserung des Auflösungsvermögens solcher Apparaturen erscheint es daher sinnvoll, Verfahren zu entwickeln, bei denen die einzelnen Schwankungsquellen in übersichtlicher Weise getrennt sind, so dass eine getrennte Herabsetzung der Einzelfehler möglich wird.

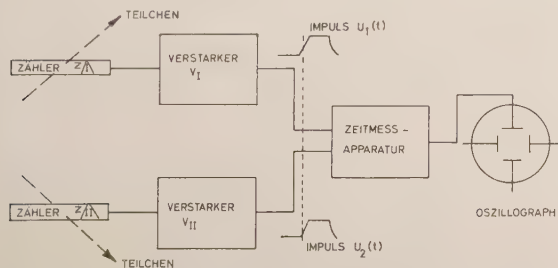


Abb. 1. Allgemeines Schema einer Koinzidenzapparatur

Das vorliegende Verfahren stellt den elektronischen Teil einer schnellen Koinzidenzstufe dar, wobei auf eine Fehleranalyse und Zurückführung der Messfehler auf prinzipiell vorhandene Schwankungsquellen Wert gelegt wurde.

† Vorgetragen auf der Tagung Deutscher Physikalischer Gesellschaften, Heidelberg, 1957.

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Betrachten wir mit Abb. 1 ein allgemeines Schema einer Koinzidenzapparatur, so stellt der Teil "Zeitmessapparatur" die eigentliche Koinzidenzstufe dar, wobei eine ja-nein-Koinzidenzanzeige stets erhalten werden kann, wenn man ein definiertes Zeitintervall auf elektronischem Wege als Koinzidenzintervall einführt.

Die Zeitmessapparatur hat dann die Aufgabe, die beiden Eingangsspannungsfunktionen $U_1(t)$ und $U_2(t)$ im Falle einer Koinzidenz, d.h. im Falle zweier kausal verknüpfter Ereignisse in den Zählern zu vergleichen und eine—zunächst vom Messverfahren abhängige—Zeitdifferenz zu definieren und zu messen. Sorgt man dafür, dass $U_1(t)$ und $U_2(t)$ ihrer analytischen Form nach identisch sind, d.h. dass also für jedes t gilt:

$$U_1(t) = U_2(t + t_0) \quad (1)$$

so reduziert sich die Aufgabe auf die Bestimmung von t_0 wobei $t_0 = T_0 + \Delta t_0$ ist, wenn T_0 die wahre zu messende Zeit und Δt_0 die Differenz der in den beiden Kanälen $Z_I V_I$ bzw. $Z_{II} V_{II}$ implizierten Gesamtfehler darstellt.

Impulse, die der Bedingung Gl. (1) praktisch genügen, lassen sich bei einer Multiplikanordnung gewinnen, wenn man die Impulse mehrfach einen Röhrenverstärker übersteuern lässt. Bei Funkenzählermessungen ist diese Bedingung bereits durch die Natur des Gasenladungsprozesses erfüllt. Wegen der Voraussetzung Gl. (1) kann die Eichung und Untersuchung des Verfahrens mit künstlichen Impulsen durchgeführt werden.

Abb. 2 zeigt ein Prinzipschaltbild der gesamten Apparatur. Impulse aus einem Quecksilberschalter gelangen über einen Vorverstärker auf zwei Kabel unterschiedlicher Länge, wobei in einem Kabel die Impulslaufzeit durch eine kontinuierlich variable Messstrecke innerhalb

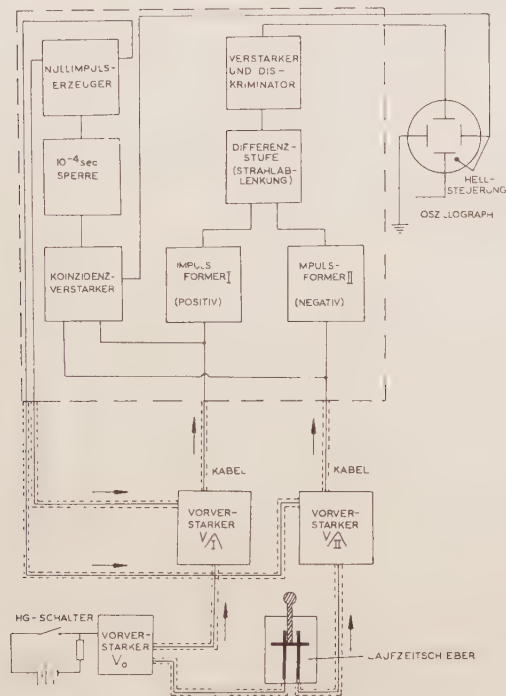


Abb. 2. Prinzipschaltbild.

eines Intervalles von 2×10^{-9} sec entsprechend einer Laufwegänderung von 60 cm verschoben werden kann. Nach Durchgang durch je einen Vorverstärker (I und II) gelangen Impulse gleicher Form jedoch mit willkürlich verschiebbarem Zeiteinsatz in die beiden Eingänge der Apparatur. Die Verstärker V_0 , V_I , V_{II} sind zweistufige RC-Röhrenverstärker, wobei jeweils die zweite Röhre gesperrt ist und durch Impulse freigesteuert wird. Durch diese Massnahme werden Störungen, die von aussen auf die Eingänge gelangen, sowie durch die Kopplungsglieder verursachtes Durchschwingen der Impulse unterdrückt. Die Amplitude der Ausgangsimpulse beträgt 20 Volt, die Impulsbreite etwa 5×10^{-7} sec und die Anstiegszeit 2×10^{-8} sec. Nach Durchgang durch die Impulsformerstufen gelangen Impulse mit Daten nach Abb. 3 auf

den Eingang einer Strahlableitkröhre E80T. In der Röhre wird ein Elektronenbündel erzeugt, dessen Richtung von der Spannungsdifferenz zweier Ablenkplatten abhängt und dessen Intensität an einer praktisch linearen Kennlinie durch ein Gitter gesteuert werden kann. Elektronen, die auf die Anode gelangen, haben vorher einen Schlitz passiert, derart, dass nur solche zum Anodenstrom beitragen, die auf ihrem Wege nur wenig abgelenkt wurden.

Seien U_A und U_B die Spannungen an den Ablenkplatten, so erhält man bei fester Gitterspannung eine um $U_A - U_B = 0$ symmetrische glockenförmige Kennlinie, wenn man den Anodenstrom I_a als Funktion von $U_A - U_B$ aufträgt. Dabei ändert sich mit der Gitterspannung nur der Ordinatenmassstab, nicht aber die Form, also speziell die Breite der Verteilung.

Wir bezeichnen jetzt mit $U_1^*(t)$ bzw. $U_2^*(t)$ die Impulse, die die Impulsformerstufen verlassen. Gibt man jetzt $U_1^*(t)$ an eine der beiden Ablenkplatten, so dass $U_A = U_1^*(t)$ wird und hält U_B fest und auf einem solchen Potential, dass im Ruhezustand der Arbeitspunkt ausserhalb des einen Fusspunktes der glockenförmigen Kennlinie liegt, so bewirkt das Auftreffen eines Impulses $U_1^*(t)$ ein kurzzeitiges Herüberstreichen des Elektronenstrahls über die Anode. Wählt man die Impulsamplitude $U_{1\max}^*(t) > 2 U_0$ wobei $2 U_0$ die Breite der Glockenkurve sei, so bewirkt die Anstiegsflanke von $U_1^*(t)$ das

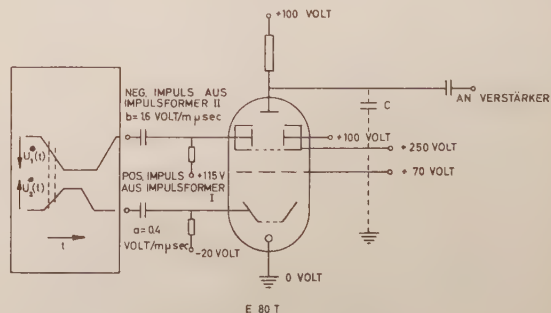


Abb. 3. Differenzstufe.

Auftreffen eines kurzzeitigen Ladungstosses an der Anode. Das Prinzip der Messung besteht nun darin, die Gitterspannung durch den Impuls

$U_2^*(t)$ zeitlich zu verändern, so dass die auf die Anode gelangende Ladung Q mit der Zeitdifferenz der Impulse variiert wird, sowie mit Hilfe eines Nachverstärkers die Grösse des Ladungsschosses zu messen.

Es soll im folgenden gezeigt werden, dass man in einem gewissen Bereich eine proportionale Abhängigkeit zwischen Q und der Zeitdifferenz der Impulse t_0 (Gl. (1)) erhalten kann. Sei $f(U_A - U_B)$ die auf 1 normierte I_a , $U_A - U_B$ Kennlinie, so dass also:

$$I_a = I_a^0 f(U_A - U_B)$$

gilt, wobei I_a^0 der Anodenstrom bei $U_A = U_B$ ist, so folgt wegen der Symmetrie der Kennlinie und der Normierung:

$$f(0) = 1 \quad \text{sowie} \quad f(U_A - U_B) = f(U_B - U_A).$$

In der Impulsformerstufe I lässt sich erreichen, dass die Anstiegsflanke des Impulses $U_1^*(t)$ innerhalb eines Bereichs $> 2 U_0$ praktisch als linear in t angesehen werden kann. Wir können also schreiben, wenn wir U_B so wählen, dass der Kennlinienbereich sich mit dem zeitlich linearen Teil des Impulses deckt:

$$f(U_A - U_B) = \varphi(t)$$

mit:

$$\varphi(\tau_0) = 1, \quad \varphi(\tau_0 - t) = \varphi(\tau_0 + t) \quad (2)$$

wenn τ_0 der Zeitpunkt sei, an dem $U_A = U_1^*(t) = U_B$ ist. Da auch die Impulsflanke $U_2^*(t)$ in einem grösseren Bereich als linear angesehen werden kann, können wir, wenn wir mit U_2^0 eine feste willkürlich vorgegebene Schwelle im linearen Teil des Impulses bezeichnen, schreiben:

$$U_2^*(t) = U_2^0 + a(t - \tau'_0)$$

wenn τ'_0 der Zeitpunkt ist, an dem $U_2^*(t)$ diese Schwelle passiert. Da ebenfalls die Gitterspannungs-Anodenstromkennlinie der Röhre linear ist, ergibt sich für den Anodenstrom:

$$I_a = \{I_2^0 + aS(t - \tau'_0)\} \varphi(t)$$

wobei S die statische Steilheit der Kennlinie und I_2^0 der dem Gitterspannungswert U_2^0 entsprechende Anodenstrom ist.

Damit ergibt sich für die gesamte während

der beiden Impulsanstiege $U_1^*(t)$ und $U_2^*(t)$ auf die Anode fließende Ladung:

$$Q = \int_{\tau^*}^{2\tau_0 - \tau^*} \{I_2^0 + aS(t - \tau'_0)\} \varphi(t) dt$$

wenn τ^* bzw. $2\tau_0 - \tau^*$ die Zeitpunkte sind, an denen die Fusspunkte der I_{a1} , $(U_A - U_B)$ -Kennlinie durchlaufen werden. Nach kurzer Umformung ergibt sich dann

$$\begin{aligned} Q &= (I_2^0 - aS\tau'_0) \int_{\tau^*}^{2\tau_0 - \tau^*} \varphi(t) dt + \\ &+ aS \int_0^{\tau_0 - \tau^*} (\tau_0 - \tau) \varphi(\tau_0 - \tau) d\tau + \\ &+ aS \int_0^{\tau_0 - \tau^*} (\tau_0 + \tau) \varphi(\tau_0 + \tau) d\tau \end{aligned}$$

so dass nach der Symmetriebedingung Gl. (2)

$$\begin{aligned} Q &= \{I_2^0 + aS(\tau_0 - \tau'_0)\} \int_{\tau^*}^{2\tau_0 - \tau^*} \varphi(t) dt = \\ &= 2 \{I_2^0 + aS(\tau_0 - \tau'_0)\} \overline{\varphi(t)} (\tau_0 - \tau^*) \end{aligned}$$

wenn mit $\overline{\varphi(t)}$ der Mittelwert von $\varphi(t)$ bezeichnet wird.

Sei $b = dU_1^*(t)/dt$ die Steilheit der Impulsflanke $U_1^*(t)$, so gilt wegen der Linearität des Impulsanstiegs $2(\tau_0 - \tau^*) b = 2U_0$ ($2U_0 =$ Breite der I_a , $U_B - U_A$ -Kennlinie) so dass:

$$Q = 2 \overline{\varphi(t)} \frac{U_0}{b} \{I_2^0 + aS(\tau_0 - \tau'_0)\}. \quad (3)$$

Es ändert sich also der auf die Anode fließende Ladungsschoss linear mit der Zeitdifferenz der Schwellendurchgänge der beiden Impulsflanken $U_1^*(t)$ und $U_2^*(t)$. Die Grösse $\tau_0 - \tau'_0$ ist aber gerade bis auf ein additives festes Glied, welches von der Lage der beiden Schwellwerte U_B bzw. U_2^0 abhängt, die zeitliche Verschiebung t_0 Gl. (1) unserer Impulse, so dass wir die Empfindlichkeit der Anordnung angeben können:

$$\frac{dQ}{dt_0} = 2 \overline{\varphi(t)} \frac{a}{b} S U_0.$$

In unserem Falle beträgt $a = 0.4$ Volt/ μsec , $b = 1.6$ V/ μsec , $S = 0.05$ mA/V, $U_0 = 7.5$ V und $\overline{\varphi(t)} = 0.4$.

Damit erhält man mit $Q = ne$:

$$\frac{dn}{dt_0} = 0.5 \times 10^6 \frac{\text{Elektronen}}{\mu\text{sec}}.$$

Die statistische Natur des Ladungsstosses bewirkt eine Schwankung des gemessenen Zeitwertes t_0 , die man erhält, wenn man die Wurzel aus der Zahl der insgesamt auf die Anode fließenden Elektronen bildet.

Man erhält für $\tau_0 = \tau'_0$ mit obigen Werten, sowie $I_2^0 = 0.5 \text{ mA}$

$$\overline{An} = \sqrt{n} = \left(\frac{2}{e} \frac{\varphi(t)}{b} \frac{U_0}{I_2^0} \right)^{\frac{1}{2}} = 3 \times 10^3 \text{ Elektronen}$$

und daraus

$$\sigma = \overline{At}_0 = \overline{An} \left(\frac{dn}{dt} \right)^{-1} = 6 \times 10^{-12} \text{ sec} \quad (4)$$

als mittleren Fehler des Messverfahrens, da, wie noch zu zeigen ist, andere Fehlerquellen von untergeordneter Bedeutung sind.

Die Ladung Q bewirkt eine Aufladung der gesamten an der Anode liegenden Kapazität um etwa 10^{-1} Volt (bei $\tau_0 = \tau'_0$) mit einer Empfindlichkeit von 5% pro $\text{m}\mu\text{sec}$. Über den Anodenwiderstand der Strahlableitkröhre erfolgt das Abfließen der Ladung, so dass man für $R = 30 \text{ k}\Omega$ Impulse von ca. 10^{-6} sec Dauer erhält, deren Amplitude dem Wert Q proportional ist. In dem auf die Zeitdifferenzstufe folgendem Nachverstärker wird Verstärkung der Impulse sowie Wegschneiden ihres unteren Anteiles erreicht, so dass man am Ausgang einen Amplitudenbereich von 0–50 Volt mit einer Zeitskala von 2×10^{-9} sec erhält. Das Röhrenrauschen der Eingangsstufen dieses Verstärkers beträgt etwa 10^{-5} Volt entsprechend einer Zeitungenauigkeit von unter 10^{-12} sec.

Die aus den Vorverstärkern eintreffenden Eingangsimpulse werden unabhängig von der Zeitmessung auf einen üblichen Koinzidenzverstärker gegeben, welcher im Falle einer Koinzidenz einen monostabilen Multivibrator anstößt. Die Zeitdauer des Multivibrator-Impulses beträgt etwa 0.5×10^{-4} sec, so dass man nach Differentiation einen um diese Zeit verzögerten Impuls erhält, den man nach Verstärkung auf beide Eingänge der Vorverstärker zurückgibt. Dadurch erhält man am Ausgang des Zeitmessteiles ein Signal, dessen Amplitude einer durch den Apparat bestimmten konstanten Zeitdifferenz entspricht. Bestimmt man die Differenz zwischen der Amplitude des

Messimpulses und derjenigen dieses Nullimpulses, so erhält man einen Wert, der frei ist von allen Fehlern, die durch langsame Kennlinienschwankungen der Verstärker sowie durch die Wirkung zeitlich veränderlicher Magnetfelder auf den Elektronenstrahl der Strahlableitstufe hervorgerufen werden. Durch einen weiteren Multivibrator mit einer Zeitkonstanten von 10^{-4} sec im Koinzidenzkreis (10^{-4} sec Sperre) wird erreicht, dass durch den Nullimpuls selbst keine weiteren verzögerten Nachimpulse ausgelöst werden können.

Abb. 4 zeigt zwei Impuls-Nullimpuls-Paare, wobei der Nullimpuls jeweils das gleiche Abszissenintervall auf dem Oszilloskophschirm

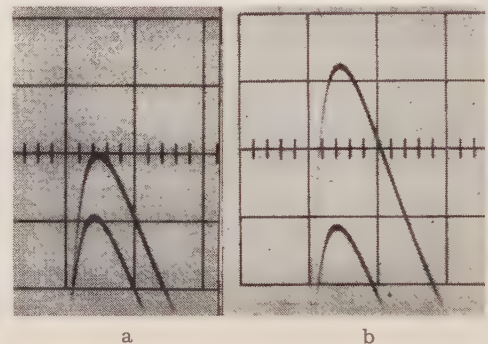


Abb. 4. Impulsoszillogramm. Unterer Impuls: Nullimpuls. Oberer Impuls: Messimpuls. Laufzeitdifferenz zwischen a und b: 2×10^{-10} sec.

überstreicht, wie der Messimpuls. Der Laufzeitunterschied der beiden Impulse beträgt, entsprechend einem Laufwegunterschied von 6 cm, 2×10^{-10} sec.

Abb. 5 zeigt zwei Fehlerverteilungskurven für 70 bzw. 80 Impulse mit einem Zeitunterschied der beiden Verteilungen von ebenfalls 2×10^{-10} sec. Die Standardfehler der beiden Verteilungen von

$$\sigma = 0.53 (\pm 0.08) \times 10^{-11} \text{ sec} \quad \text{bzw.}$$

$$\sigma = 0.68 (\pm 0.07) \times 10^{-11} \text{ sec}$$

sind mit dem berechneten Wert aus Gl. (4) in Übereinstimmung.

Abb. 6 zeigt die Linearität des Verfahrens. Die Krümmung im oberen Teil der Eichkurve ist auf die Nichtlinearität der Kennlinie der letzten Verstärkerröhre zurückzuführen und

kann im Bedarfsfall vermieden werden. Der Messbereich hängt ersichtlich von der Linearität und der Flankensteilheit des Impulses $U_2^*(t)$ ab und kann natürlich je nach Anwendungszweck der Methode geeignet gewählt werden.

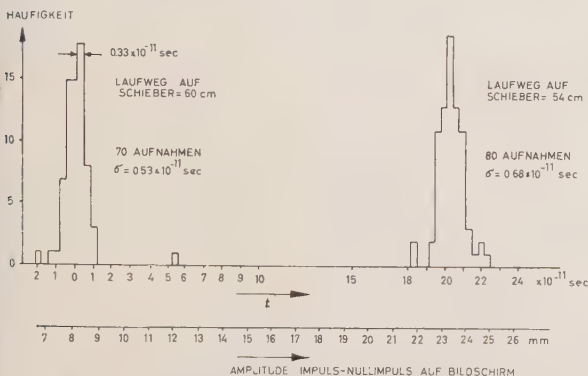


Abb. 5. Fehlerverteilungskurven für zwei verschiedene Impulslaufzeiten, Laufzeitdifferenz 2×10^{-10} sec.

Die Eichung der Apparatur ist einfach durchführbar durch Ausmessung der Relation Impulshöhe-Schieberstellung, wenn man vor-

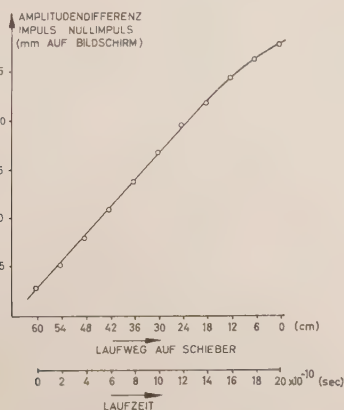


Abb. 6. Eichkurve.

aussetzt, dass die Ausbreitungsgeschwindigkeit der Impulse auf dem Schieber gleich der Lichtgeschwindigkeit ist. Zur Kontrolle genügt

es wegen der Linearität der Eichkurve nach Abb. 6 nachzuweisen, dass diese Voraussetzung für den vollen Schieberbereich (2×30 cm Laufweg, entsprechend 2×10^{-9} sec) gültig ist. Zu diesem Zweck wurde die Horizontalablenkung des Oszillographen durch den Impuls $U_1^*(t)$ ausgelöst, während $U_2^*(t)$ auf die Messplatten gegeben wurde. Es wurden die Anstiegsflanken je eines Impulses bei den beiden extremen Schieberstellungen nacheinander photographiert, und die zeitlichen Verschiebungen ausgemessen. Danach ergab sich $v_{\text{Schieber}} = c \pm 5\%$, so dass der während dieser Arbeit benutzte Zeitmassstab mit dieser Genauigkeit bestimmt ist.

Die Einführung des Nullimpulsvergleichs hat zur Folge, dass durch die 10^{-4} Sekunden-sperrung künstlich eine Totzeit von dieser Grössenordnung in die Apparatur eingeführt wird, mithin das Verfahren in dieser Genauigkeit nur für kleine Impulsraten, z.B. Funkenzählermessungen, geeignet ist. Die Anwendung des Verfahrens für Szintillationszählermessungen wird vorbereitet. Nach bereits durchgeführten Experimenten erhält man ohne Verwendung eines Vergleichsimpulses ein zeitliches Auflösungsvermögen des elektronischen Teiles von etwa 3×10^{-11} sec mit einer Erholungszeit der Apparatur von ca. $1 \mu\text{sec}$.

Die Arbeit wurde durchgeführt im Physikalischen Institut der Technischen Hochschule Braunschweig. Dem Direktor des Instituts Herrn Prof. Dr. G. Cario sowie den Herren Dr. H. Fack und Dr. A. Lohmann danke ich für zahlreiche Diskussionen. Dem Hannoverschen Wirtschaftsministerium gebührt mein Dank für die Mittel zur Durchführung dieser Arbeit.

A LOGARITHMIC, CONSTANT PERCENT ERROR, PULSE HEIGHT ANALYZER

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A single channel pulse-height analyzer with a dead time of about $0.15 \mu\text{sec}$ is described. The channel width is determined by the passive characteristics of a delay line and is a

constant percentage of the discriminator setting. An important feature of the device is a paralysis circuit. Circuit diagrams and calibration curves are given.

1. Introduction

The need for fast and drift-free pulse-height analyzers in nuclear physics hardly requires to be stressed: conventional forms of single channel discriminators¹⁻⁵) usually resort to 'kicksorting': i.e. two threshold discriminators

followed by an anti-coincidence, while, of course, defining channel width by means of a standard pulse is also widely employed⁶⁻⁸).

The present analyzer differs radically from the above mentioned ones and is a development of the ideas set forth in a recent article⁹): the

BLOCK DIAGRAM OF THE PHALCO PULSE-HEIGHT ANALYZER

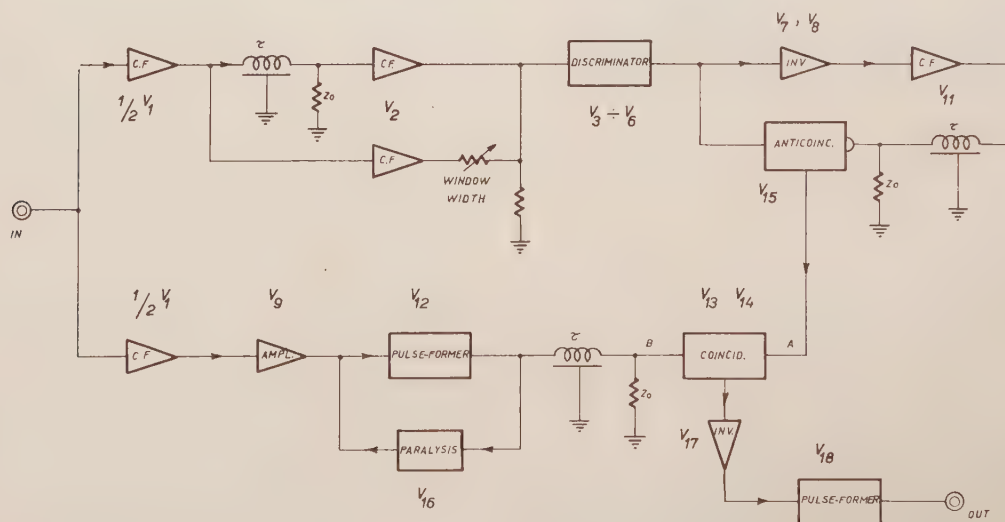


Fig. 1 †

† The abbreviation PHALCO on the headings is short for: Pulse Height Analyzer with Line Coding.

¹) R. D. Amado and R. Wilson, Journ. Sc. Instr. **34** (1957) 205.

²) E. Fairstein and E. M. Porter, Rev. Sc. Instr. **23** (1952) 650.

³) E. Fairstein and F. M. Porter, Rev. Sc. Instr. **27** (1956) 549.

⁴) F. J. M. Farley, Journ. Sc. Instr. **31** (1954) 241.

⁵) F. C. Park, Journ. Sc. Instr. **33** (1956) 257.

⁶) E. Gatti and F. Piva, Nuovo Cimento Ser. IX, **10** (1953) 984.

⁷) E. Gatti, Nuovo Cimento Ser. IX, **11** (1954) 153.

⁸) S. Colombo, C. Cottini and E. Gatti, Nuovo Cimento Ser. X, **5** (1957) 748.

⁹) A. Alberigi-Quaranta, C. Bernardini and I. F. Quercia, Nuclear Instruments **3** (1958) 201.

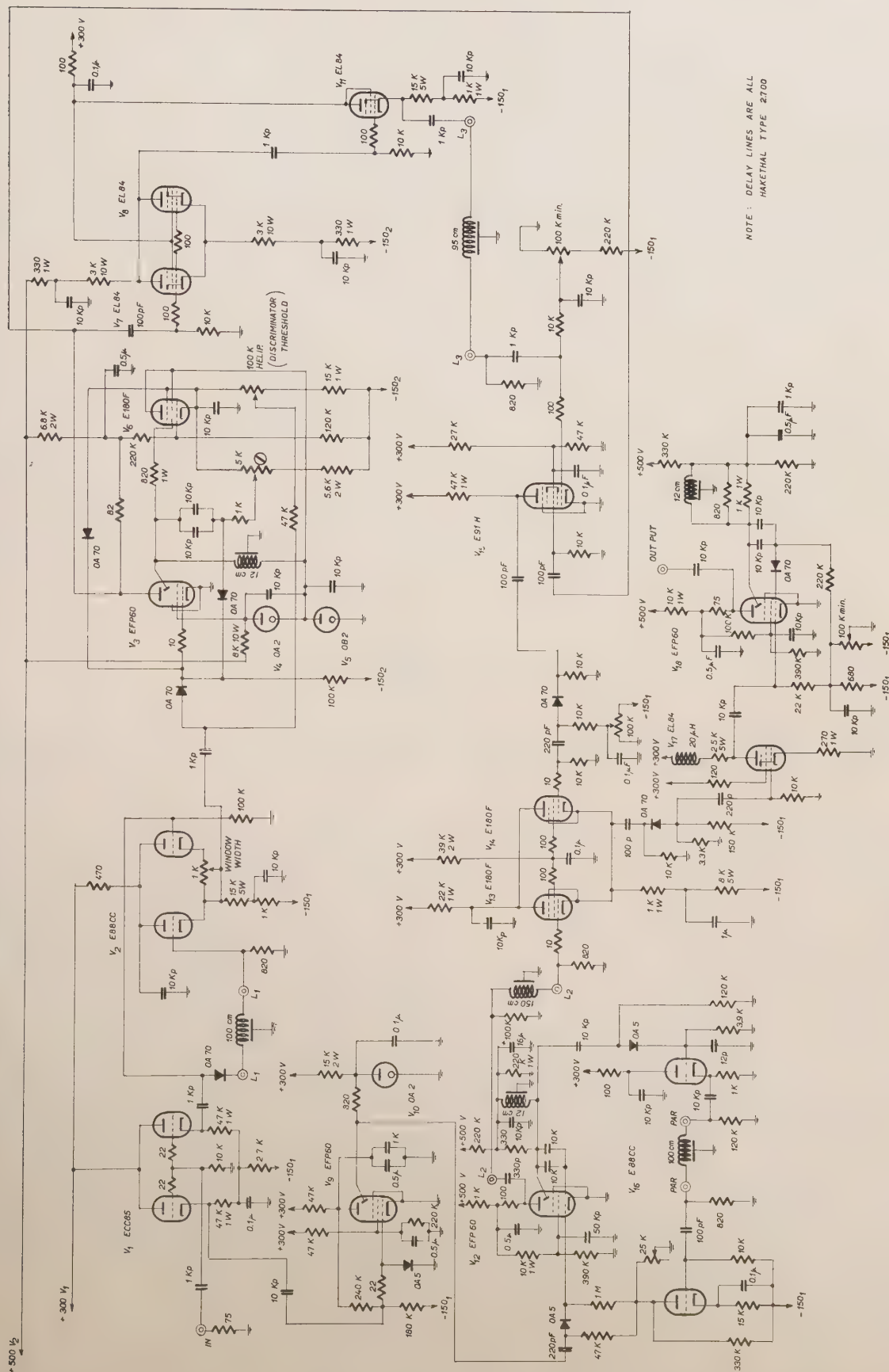


Fig 2

incoming pulse is attenuated and delayed by a matched length of line: both the original pulse and the delayed one are injected into a threshold discriminator: this means that for every input pulse, two pulses are fed to the discriminator at different times: the first pulse of amplitude V_0 at a time $t = 0$, the second of amplitude $V_0 \exp(-\gamma L)$ at a time $T = \tau$, where τ and γL denote delay and attenuation respectively.

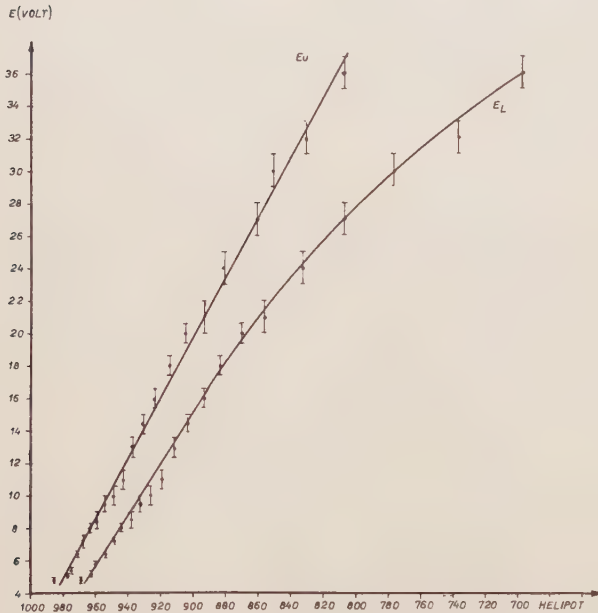


Fig 3

If we denote the discriminator bias by V_t , the discriminator will trigger

twice if $V_t < V_0 \exp(-\gamma L) < V_0$

once if $V_0 \exp(-\gamma L) < V_t < V_0$

never if $V_0 \exp(-\gamma L) < V_0 < V_t$.

In other words, every time the discriminator fired only once we know that the input pulse had an amplitude V_0 such that $V_t < V_0 < V_0 \exp(-\gamma L)$. Subsequent circuitry is designed to give an output pulse if, and only if, the discriminator fired only once.

2. Circuit Description

The block diagram of the analyzer is shown in fig. 1. Its operation may be summarized as follows: an input pulse reaching IN is cathode

followed and delayed reaching the threshold discriminator and is also branched through a variable-gain C.F. so as to control the channel width and again injected in the discriminator; two pulse thus reach the discriminator as outlined previously. The discriminator output is fed to an anti-coincidence circuit both directly and through a delay τ . This insures an output pulse from the coincidence at a time τ after the

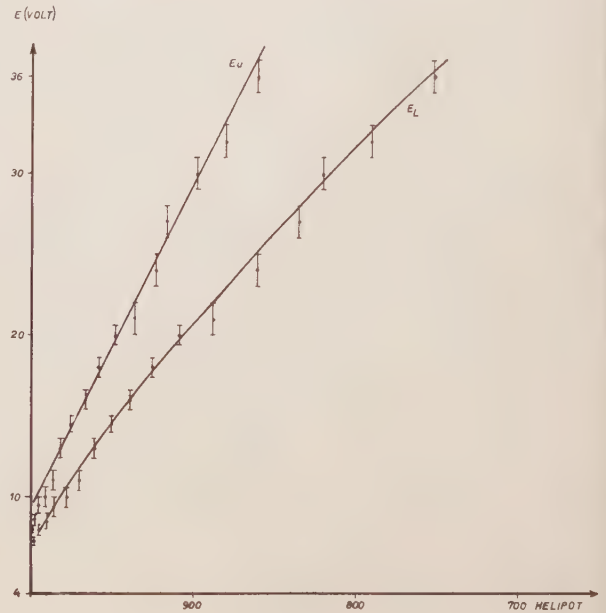


Fig. 4

last pulse coming from the discriminator; i.e. if the discriminator does not trigger there is no pulse in A, if the discriminator triggers once a pulse appears in A a time τ after the input pulse; finally, if the discriminator fired twice a pulse appears in A at time 2τ .

Neglecting the paralysis circuit for the moment, one sees that the input pulse is also cathode followed, amplified, shaped and delayed by τ before it is injected in the coincidence input (point B). The coincidence will therefore produce an output pulse only if the discriminator triggered only once producing a pulse injected at the input A at time τ . The coincidence (resolving power is about 10 μsec) output is shaped again before being allowed to reach the output terminals.

An important feature of this circuit is a "paralysis" device which shuts the analyzer off during its dead time (about $0.15 \mu\text{sec}$). This proves useful in analyzing random pulses because the discriminator might not be able to differentiate between an artificially delayed pulse and a second input pulse occurring soon after the first one. Accurate knowledge of dead time is also of help in making theoretical corrections. Paralysis is introduced in the nonlinear channel by V_{16} in the following manner: positive pulses coming from the dynode of V_{12} are stretched, cathode followed, delayed and inverted by V_{16} and subsequently applied to the grid of V_{12} : the latter is thus kept well below cut-off during dead-time and consequently will not respond to any further input pulse.

The complete diagram of the discriminator is shown in fig. 2.

3. Performance

As a threshold discriminator, the Moody circuit¹⁰) was found to give stable and reliable operation: the linearity of the single-channel discriminator is evident from the calibration curves, (figs. 3-4) where one can also see that the fractional channel width of the analyzer is constant as was shown in⁹).

Drift of the discriminator threshold was about 0.1 V, while drift in channel width was much smaller than this figure. Dependence in pulse shape and rise time are slight, while calibration of the single-channel analyzer does depend on pulse duration between 10 and $100 \text{ m}\mu\text{s}$ as evidenced by the calibration curves. The analyzer as a whole is, of course only as good as its threshold discriminator; the same principle of operation could be used to build a faster analyzer as soon as faster threshold discriminators become available.

¹⁰) N. F. Moody, G. J. R. MacLusky and M. O. Deighton, Elec. Engng. **24** (1952) 214.

VACUUM DEPOSITION OF URANIUM ON THIN ORGANIC BACKINGS FOR NUCLEAR SPECTROSCOPIC USE

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and

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Received 5 June 1959

A method has been developed for the preparation of uranium converters for use in high resolution gamma spectroscopy. Vacuum deposition was found to be preferable because homogenous films can be obtained on organic

backing materials. The present method enables metallic uranium converters to be produced with a thickness up to 2 mg/cm².

1. Introduction

For high resolution spectroscopy it is of great interest to have converters on organic backings of low Z -value. This enables several strips of the metal to be deposited side by side, while remaining electrically insulated from each other. With converters of this type it is possible to apply a potential gradient, as is necessary in certain cases¹). Because of the Z^5 variation of the photo cross-section, uranium has often been used as converter material to get as high an intensity as possible. The conventional method²) of producing uranium converters is to paint uranyl nitrate solution on aluminium foils and heat them to about 500° C. This process reduces the nitrate to oxide. However, this method is rather laborious and the oxide instead of the metal is a disadvantage in high resolution work. It is also difficult to use backings thinner than 20 mg/cm². Films of organic compounds such as zapon and mylar are easily obtainable as thin foils of relatively great strength, in particular mylar, which is produced commercially in various thicknesses. Mylar as a plastic compound cannot of course be subject to a temperature of 500° C, which rules out the painting technique. Other methods have been described elsewhere, and only a brief

summary is necessary here. Electrodeposition of uranium onto the noble metals has been described³). If mylar is to be used as a backing in electrodeposition, one must first evaporate a metal substrate that has a low Z -value to act as cathode. Such metals e.g. aluminium will generally dissolve in the electrolyte. Even if one uses a noble metal as the substrate, (which would naturally complicate the interpretation of the spectra to a high degree) the method is troublesome and it is difficult to obtain uranium films of sufficient homogeneity. The slurry technique⁴), which is perhaps the simplest method, requires very little apparatus. Unfortunately, even if stringent precautions are taken, this method can be a serious health hazard (very fine oxide dust is required). Also, converters produced in this manner are rather poor with respect to homogeneity and have very bad adhesion properties. Briefly, a glass tube of

¹) K. E. Bergkvist, to be published.

²) K. M. Glover and P. Borell, *J. Nuclear Energy* 1 (1955) 214;

T. Novakov, S. Hultberg and B. Andersson, *Arkiv för Fysik* 13 (1958) 119.

³) A. Graves and D. Froman, *Miscellaneous Phys. and Chem. Techn. of the Los Alamos Project* (McGraw-Hill, 1952) 22.

⁴) Chapter I in ref. ³).

the required dimensions is placed in contact with the backing, oxide dust in solution is pipetted into the tube and allowed to settle out on the backing. After the removal of surplus solution, the deposit is dried by means of a heat lamp. Evaporation, where possible, is by far the best method of obtaining homogeneous deposits of uranium on organic backings. There

2. General Arrangement

The arrangement shown in the figure is that used for producing the converters. A tungsten strip $0.1 \times 5 \times 20$ mm, is formed into a boat by two V-shaped water cooled copper blocks. The thickness of the tungsten was found to be rather critical, and experimentation showed that 0.1 mm was the most suitable. The crucible

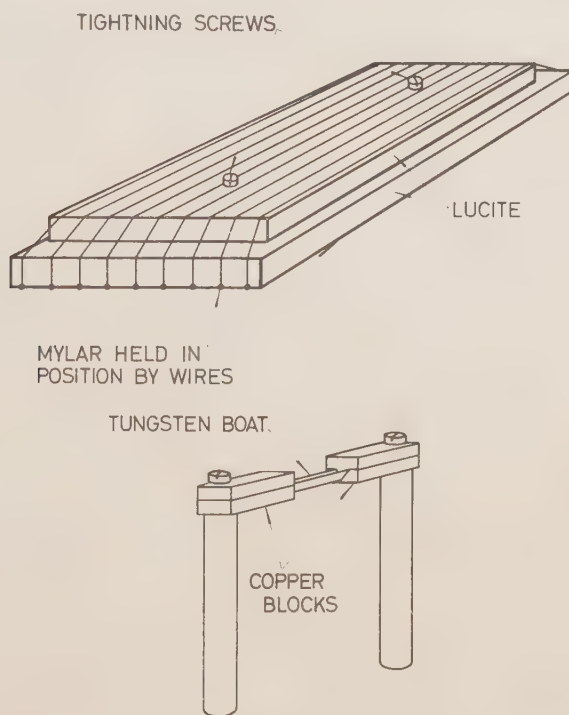


Fig. 1.

are, however, certain difficulties which must first be overcome. One group⁵⁾ in England, succeeded in evaporating uranium onto aluminium foils by using three 1 mm diameter tungsten wires which were heated by a current of 150 A over a period of 15 minutes. During such a long evaporation time, a considerable amount of heat must be transferred to the foil by radiation. The use of plastic backings would be very difficult with the above arrangement. As a consequence of an attempt to increase the resolution of a double focusing spectrometer⁶⁾, experiments in the evaporation of uranium metal onto plastic films of mylar have been carried out.

dimensions and method of support gives a very concentrated heat source, a desirable feature when working with uranium. The backing support is situated 65 mm above the crucible. High speed pumps and a liquid air trap enable a pressure of 10^{-6} mm Hg to be maintained during the preparation. With the crucible described, a current of 40 A for 10 sec was sufficient for the deposition.

3. Backing Support

The first attempts at deposition were made using a glass plate as the receiving backing, and

⁵⁾ K. K. Damodaran, Brit. J. appl. Phys., 7 (1956) 322.

⁶⁾ K. E. Bergkvist, to be published.

as previously stated, a current of 40 A was used. Uranium films of high reflecting power were obtained having an estimated thickness (by weighing) of 0.2 mg/cm^2 . The radiation (measured with end-window counter) showed this to be practically pure uranium. These films oxidized in 10 to 20 min on exposure to atmosphere. Regardless of the amount of metal loaded in the crucible, it appeared impossible to obtain thicker films at one evaporation, probably due to alloying of the uranium and tungsten. The next step, that of obtaining deposits on mylar, was thought to require cooling, and a mounting block similar to that shown in the figure but made of copper and water cooled was constructed. The backing material, 1.8 mg/cm^2 mylar, is held in position by winding nine turns of 0.3 mm copper wire, spaced 3 mm apart, round the block. This arrangement also serves as a mask, which when removed, leaves strips of film electrically insulated from each other, thus allowing for a potential gradient to be applied to the converter as a whole. Unfortunately, when attached to the copper block, the mylar was destroyed during the evaporation. However, when a second mylar backing was attached to a glass plate, a film was obtained. This suggested that destruction of the film was due to reflection of radiant heat from the metal backing support. To test this idea, a piece of lucite, 3 mm thick, was placed over the crucible and a metal block with highly reflecting surface placed in the centre. Examination of the plate after the evaporation, revealed good deposits of the metal on the areas not effected by the

reflecting surface, the latter part however, was badly burnt. This experiment was repeated several times with the same result. Finally, attempts were made to deposit the metal on aluminium foils, but regardless of the amount of metal used, only about one third was deposited as compared with organic materials. Further, unless the foils were placed at a considerable distance from the crucible they were badly burnt. The arrangement finally arrived at is that shown in the figure, with the mounting block made of lucite. In order to obtain a film of approximately 1 mg/cm^2 , it was necessary to reload the crucible five times. It was found that if the film was exposed to air, while reloading took place, the oxide formed on the deposit prevented good adhesion for the following deposits. As a consequence of this, a device was constructed for reloading the crucibles in vacuum. Three crucible positions were used, each one capable of three evaporations. A fourth crucible was employed for depositing an aluminium film 1 mg/cm^2 as shield against oxidation. This latter difficulty, though not prevented, can be retarded considerably in the above manner.

Acknowledgement

The authors wish to thank Professor Manne Siegbahn of the Nobel Institute of Physics, Stockholm and Professor Kai Siegbahn of the Institute of Physics, Uppsala for their interest in this work. We should also like to thank Doctor J. H. Hamilton for his comments on the manuscript.

MULTIRANGE DELAY LINE FOR APPLICATION IN BETA-GAMMA COINCIDENCE STUDIES

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Received 5 May 1959

The circuit of a counting signal delay unit with a range of 0 to 11.4 μsec in steps of 0.1 μsec is described. A continuously adjustable delay line (0.05 μsec per cm) covers a

range of 1.5 μ sec. The construction and design formulae of the latter delay line is given.

1. Introduction

When beta-gamma coincidence analysis is done with a Geiger counter and a scintillation counter for the registration of beta particles and gamma rays, respectively, it is often necessary

meter, which is also fitted with a scintillation head immediately behind the source holder. These different Geiger counters have different internal signal delays which require a variable delay line for the scintillation unit.

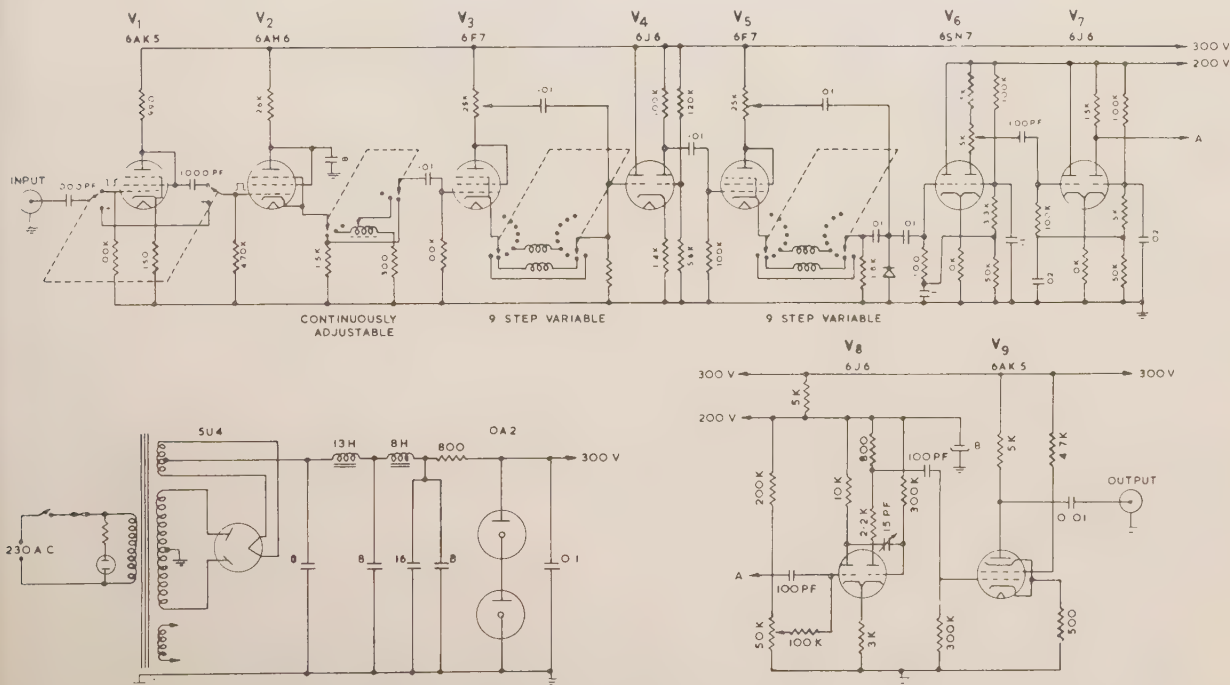


Fig. 1. Circuit diagram of delay line unit: 0 to 11.4 μ sec.

to be able to delay the scintillation channel with respect to the Geiger counter channel^{1, 2)}. At this institute Geiger counters of different design are used in the L.K.B. Siegbahn-Slätis beta spectro-

† This work was done under the auspices of the South African Atomic Energy Board in the laboratories of the Council for Scientific and Industrial Research.

A “dummy” delay line to compensate for the electronic signal delay in the delay unit proper is used in the β -channel.

¹) P. W. de Lange, Die Verval van die UX-kompleks, D. Sc. Thesis, University of Pretoria (Nov. 1958).

2) H. Schneider, P. W. de Lange and J. W. L. de Villiers, On the beta decay of uranium X2, *Nuovo Cimento*, in press.

2. Description of Circuit

The circuit diagram of the delay unit is given in fig. 1. Tube V_1 , with unit amplification serves the purpose of inverting negative input pulses; for positive input pulses V_1 is bypassed. V_2 is used as a cathode follower for impedance matching of the first delay line. This delay line, which has been designed and constructed in this laboratory and which is described below, is continuously adjustable ($0.05 \mu\text{sec}$ per cm) from 0 to $1.5 \mu\text{sec}$, and has a characteristic impedance of 300 ohms.

The pentode section of V_3 is used as a cathode follower for impedance matching to the next set of delay lines, which can be chosen in steps of $0.1 \mu\text{sec}$ up to $0.9 \mu\text{sec}$. Various lengths of delay line cable type KD261 have been used. An adjustable signal from the plate of V_3 is employed to suppress the unwanted signal that leaks through the delay line due to the capacitance between neighbouring windings. An optimum signal adjustment can be obtained so that no resetting is necessary when different delay times are chosen.

A cathode coupled stage V_4 is used to amplify the signal to compensate for signal attenuation in the preceding delay lines. An amplification factor of about 8 is desired.

Stages V_5 and V_6 serve the same purpose as V_3 and V_4 , for the next set of delay lines ($0.9 \mu\text{sec}$; in steps of $1 \mu\text{sec}$). Various lengths of delay line cable type KD260 have been used for these. A crystal diode 1N34 is used to suppress any negative overshoot.

V_7 is also a cathode coupled amplifier producing a sufficiently large pulse to trigger the pulse shaper V_8 which has a variable trigger level.

Stage V_9 is the final amplification and output stage and produces a negative output pulse.

The power supply is of conventional design. The two types of delay line cable have been supplied by Federal Telephone and Radio Co., U.S.A.

The delay unit has been tested with pulses between 1 and 20 volts with a pulse length between 0.1 and $10 \mu\text{sec}$. There is an inherent dead time of less than $2 \mu\text{sec}$ and the unit has

been used with count rates up to 1000 per second without losses.

The output signal has a rise time of $0.5 \mu\text{sec}$, a length of $1 \mu\text{sec}$ and a delay time of $0.4 \mu\text{sec}$. The output signal has an amplitude of 7 volts negative.

The range of this signal delay unit is 0 to $11.4 \mu\text{sec}$ when the internal delay, apart from any delay lines, is $0.5 \mu\text{sec}$ and has operated for long periods without failure.

3. Continuously Adjustable Delay Line

As such a variable delay line often comes in handy for testing resolution of coincidence-circuits etc., a brief outline of construction and design is given below:

The ceramic core of a rheostat was replaced by a brass tube covered with a single layer of insulation and of identical outer diameter. Over this a single layer of enamelled copperwire was closewound over the entire length. Amphenol connectors were fitted to the one end of the winding and the slider. The open end of the line was terminated by a carbon potentiometer adjusted for minimum pulse distortion—the slider makes contact with the winding where the enamel insulation has been scraped off. The line was calibrated with a Tektronix oscilloscope, Model 517.

Design formulae: Delay

$$\Delta t = l \sqrt{LC}$$

Characteristic impedance

$$R_0 = \sqrt{L/C}$$

$$L = \mu_0 N^2 A \quad (\text{cylinder-helix winding})$$

$$C = \frac{2}{3} \times \frac{2\pi\epsilon_0\epsilon_r}{\ln \frac{r_a}{r_i}} \quad (\text{cylinder capacitance})$$

where

l = length of line in metres.

L = inductance per metre.

C = capacitance per metre.

μ_0 = permeability of vacuum = 4×10^{-7} volt·sec/amp·metre.

N = turns per metre.

A = enclosed area.

ϵ_0 = permittivity of vacuum = 8.86×10^{-12} coulomb²/metre²·newton.

r_a = internal radius of outer cylinder.

r_i = external radius of inner cylinder.

ϵ_r = dielectric constant of medium.

LIST OF PARTICLE-ACCELERATOR INSTALLATIONS:

ADDENDA AND ERRATA

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Received 20 January 1959

Communications received by the author after recent publication of a list of particle-accelerator installations operating throughout the world have yielded additional information and pointed out certain errata¹⁾. The addenda and corrected information are given below.

ADDENDA

I. DIRECT CURRENT MACHINES

In the United States

Location	Type	Dimensions		Particles accelerated	Energy (MeV)
² Argonne National Laboratory, Lemont, Ill.	Van de Graaff	n.a.		e, p, d	3.0
³ General Electric Co., General Engineering Laboratory, Schenectady, N.Y.	Cockcroft-Walton	3.6-ft	accelerating tube	d	0.4
	†Cockcroft-Walton	15-ft	accelerating tube	e	1
	†Cockcroft-Walton	15-ft	accelerating tube	d	1
⁴ Vanderbilt University, Nashville, Tenn.	Cockcroft-Walton	n.a.		p, d, α	0.4
⁵ Wesleyan University, Middletown, Conn.	Cockcroft-Walton	3-ft	accelerating tube	d	0.16

† Under construction.

1) Gerald A. Behman, Nuclear Instruments 3 (1958) 181.
2) J. R. Wallace, Argonne National Laboratory, private communication (December 1958).
3) R. S. Rochlin, General Engineering Laboratory, General Electric Co., private communication (February 1959).
4) C. D. Curtis, Vanderbilt University, private communication (February 1959).
5) F. Boley, Wesleyan University, private communication (January 1959).
6) C. M. Raggio, Laboratoria de Fisica Nuclear, Santiago, Chile, private communication (December 1958).
7) P. Silvy, Soci  t   Anonyme de Machines Electrostatique, Grenoble, France, private communication (December 1958).
8) R. E. White, High Voltage Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., private communication (January 1959).
9) R. M. Chaudri, Government College, Lahore, Pakistan, private communication (March 1959).
10) I. Yenicay, Istanbul University, Istanbul, Turkey, private communication (January 1959).
11) E. Walter and K. F. Malsch, Siemens-Reiniger-Werke Aktiengesellschaft, Erlangen, Germany, private communication (February 1959).

Outside the United States

Location	Type	Dimensions		Particles accelerated	Energy (MeV)
<i>Chile</i>					
⁶ Laboratoria de Fisica Nuclear, Santiago	Cockcroft-Walton	12-ft	accelerating tube	p, d, α	0.72
<i>France</i>					
⁷ Centre d'Études Nucléaires de Saclay, Saclay	Felici	0.41-m	accelerating tube	p, d	0.15
	†Felici	1.9-m	accelerating tube	p, d	0.6
	Cockcroft-Walton	n.a.		p, d	0.3
⁷ Compagnie Francaise de Raffinage	Van de Graaff	n.a.		e	2
⁷ Direction des Études et Fabrications d'Armement, Paris	Felici	0.41-m	accelerating tube	p, d	0.15
⁷ Ecole des Hautes Études, Paris	Felici	n.a.		p, d	0.3
⁷ Faculte des Sciences, Alger	Felici	1.9-m	accelerating tube	p, d, e	0.6
⁷ Faculte des Sciences, Grenoble	Felici	n.a.		p, d	0.3
	Felici	n.a.		e	1
⁷ Faculte des Sciences, Paris	Felici	1.9-m	accelerating tube	p, d, e	0.6
	Cockcroft-Walton	n.a.		e	1
⁷ Faculte des Sciences, Strasbourg	Felici	n.a.		p, d	0.3
	Felici	0.41-	accelerating tube	p, d	0.15
⁷ Laboratoire de Synthese Atomique, Ivry	Felici	1.9-m	accelerating tube	p, d, e	0.6
	Felici	n.a.		p, d	0.3
<i>New Zealand</i>					
⁸ Auckland, University, Auckland	Cockcroft-Walton	n.a.		p, d	0.6
⁸ Otago, University, Dunedin	Van de Graaff	n.a.		n.a.	0.7
<i>Pakistan</i>					
⁹ Government College, Lahore	Cockcroft-Walton	12-ft	accelerating tube	p, d, α	1.2
<i>Turkey</i>					
¹⁶ Istanbul, University, Istanbul	Cockcroft-Walton	2.5-m	accelerating tube	p, d	0.8

II. INDUCTION MACHINES: BETATRONS

Outside the United States

Location	Orbit radius	Particles accelerated	Energy (MeV)
<i>Belgium</i>			
¹¹ Universite-Klinik Prof. van Vaerenbergh, Ghent	10 cm	e	15
<i>France</i>			
¹¹ Laboratoire Central des Industries Électriques, Paris	10 cm	e	15
<i>Germany</i>			
¹¹ Czerny-Krankenhaus, Heidelberg	10 cm	e	15
¹¹ Firma Mannesmann, Duisburg-Huckingen	10 cm	e	15
¹¹ Med.-Universitätsklinik, Erlangen	10 cm	2	15
¹¹ St. Georg-Krankenhaus, Hamburg	10 cm	e	15

Location	Orbit radius	Particles accelerated	Energy (MeV)
¹¹ Städt. Krankenanstalten, Düsseldorf	10 cm	e	15
¹¹ Strahlenklinik Prof. Janker, Bonn	10 cm	e	15
¹¹ Universitäts-Frauenklinik, Hamburg	10 cm	e	15
¹¹ Universitäts-Hautpoliklinik, Göttingen	10 cm	e	15
¹¹ Universitäts-Klinik, München	10 cm	e	15
¹¹ Universitäts-Strahleninstitut, Marburg	10 cm	e	15
¹¹ Universitäts-Strahleninstitut, Tübingen	10 cm	e	15
<i>Italy</i>			
¹¹ Centro Tumori, Cagliari	10 cm	e	15
¹¹ Centro Tumori, Chieti	10 cm	e	15
¹¹ Centro Tumori, Palermo	10 cm	e	15
¹¹ Consorzio Cura Tumori, Udine	10 cm	e	15
¹¹ Istituto die Radiologia dell'Universita, Rome	10 cm	e	15
¹¹ Istituto Regina Elena, Rome	10 cm	e	15
¹¹ Ospedale San Lorenzo, Borgo Valsugana	10 cm	e	15
<i>Mexico</i>			
¹¹ Centro Medico, Mexico City	10 cm	e	15
<i>Sweden</i>			
¹¹ Radiumhemmet, Stockholm	10 cm	e	15

Corrections

Certain fixed-field alternating-gradient (FFAG) accelerators were included in the synchrotron group in the recently published list by this author¹⁾. McMillan has pointed out that, under the classification system suggested by him for this list, all FFAG accelerators belong in the cyclotron class because the field does not vary as a function of time¹²⁾. Accordingly, the FFAG machines listed for the Midwestern Universities Research Association, Madison, Wis. should be included in the cyclotron group in this list.

In the classification system used, two general types of cyclotrons were indicated. These are continuous-wave (CW) and frequency-modulated (FM) machines. It should be noted that the FM class of cyclotrons may be referred to alternatively as synchrocyclotrons.

The dimensions of the larger of two Van de Graaff machines at Argonne National Laboratory, Lemont, Illinois were listed incorrectly. This machine has a 15-ft accelerating tube, can accelerate protons, deuterons, or alpha particles, and has a maximum energy of 4.5 MeV²⁾.

D.C. machines listed at the Centre d'Etudes Nucléaires, Grenoble, France and at the Laboratoire de Physique Atomique et Moléculaire, Collège de France, Paris are Felici-type accelerators rather than Van de Graaff generators⁸⁾. As contrasted with the belt system of charge transport of the Van de Graaff machines, the Felici machine uses a dielectric cylinder which rotates about a slightly conducting glass stator. Thin steel strips charge and discharge the rotor as a result of induction of metallic inductors within the glass cylinder. For improved efficiency, the machine usually operates under a high pressure¹³⁾.

The proper location of the betatron listed for the Knolls Atomic Power Laboratory is General Engineering Laboratory, General Electric Company, Schenectady, N.Y.³⁾.

The 4-MeV Van de Graaff machine and 32-MeV proton linac formerly at University of

¹²⁾ Edwin M. McMillan, Lawrence Radiation Laboratory, private communication (1958).

¹³⁾ Emile Labin, *Electromechanical Design* 2, No. 11 (1958) 24.

California in Berkeley have been moved to the University of Southern California at Los Angeles, California.

Acknowledgments

The author is deeply grateful to the scientists of various countries who provided the new and

revised information published here. Thanks are due Dr. Edwin McMillan for helpful suggestions and to other members of the staff of the Lawrence Radiation Laboratory for their aid.

This work was done under the auspices of the U.S. Atomic Energy Commission.

BOOK REVIEW

Encyclopedia of Physics. Vol. XLV. *Nuclear Instrumentation II* (Editor S. FLÜGGE) Springer Verlag. DM 128,—

In this volume there are nine contributions dealing with different types of nuclear detectors.

H. W. Fulbright's paper, *Ionization Chambers in Nuclear Physics*, contains an excellent survey on the many different ways in which ionization chambers have been applied for fundamental nuclear research. Due consideration is given also to the important use of ionization chambers as radiation survey instruments and pocket dosimeters. S. A. Korff has written the chapter on *Geiger Counters*. *The Proportional Counter as Detector and Spectrometer* is treated in a most interesting paper by S. C. Curran. The remarkable achievements obtained by Professor Curran and his co-workers are illustrated in several diagrams which show the resolution of closely spaced low energy lines and also the Kurie plot of H^3 , linear down to below 1 keV. It is evident that the proportional counter spectrometer has now been developed into a most powerful instrument for nuclear spectroscopy. *Scintillation and Čerenkov Counters* are treated by W. E. Mott and R. B. Sutton. Their paper contains an intensive compilation of data of importance for the experimentalist. Photomultiplier types and characteristics are given and the merits of various phosphors are discussed in detail. A great number of diagrams are reproduced which show calculated efficiencies of NaI crystals under various geometrical conditions are reproduced. Čerenkov counters of various types are discussed with references to important applications in high energy physics.

A special chapter by S. De Benedetti and R. W. Findley has been devoted to *The Coincidence Method*. Various types of coincidence circuits are discussed and circuit diagrams are given. Chronotrons and time-to-pulse height-

converters are briefly mentioned. Finally, some of the applications of coincidence method are reviewed. These include the delayed coincidence technique for the measurements of short time intervals.

The following three chapters deal with *Cloud Chambers* (C. M. York), *The Bubble Chamber* (D. A. Glaser) and *Nuclear Emulsions* (M. M. Shapiro). They all three contains beautiful photographs of "tracks". These three track-forming detectors are to a great extent complimentary and to some extent competitive. All three authors are, of course, quite enthusiastic about the merits of their special technique. It is perhaps significant, however, that only in Glaser's paper is there a direct comparison between the potentialities of the track forming detectors.

The last two chapters are devoted to neutron detectors. H. H. Barschall's contribution (*Detection of Neutrons*) deals with neutrons of energies below 20 MeV. The basic interactions used for detection are surveyed. The following section deals with detecting devices. Comparisons of various neutron monitors and of different types of fast neutron spectrometers are given. The various methods used for the measurement fast neutron fluxes are compared. *High Energy Neutron Detectors* (20–700 MeV) are discussed by R. T. Siegel. In the first section energies and intensities of presently available high energy neutron beams are surveyed and the various types of interactions are discussed. The following section deals with the detection devices developed. Finally, in the last section some comparisons of different detector systems have been made.

This volume of the Encyclopedia is full of information and advice of importance for the experimental nuclear physicist. The contributions are of the highest standard and very up to date.

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